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Russellite, a new British mineral.

(With Plate II.)

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With a note on the occurrence and the accompanying minerals.

By Arthur Russell.

[Read November 4, 1937.]

IN May, 1936, a quantity of pale yellow, rounded fragments, averaging 7 mm. across, was submitted to us by Mr. Arthur Russell for examination, with the information that the material came from the Castle-an-Dinas wolfram mine, and contained bismuth and tungsten. Chemical and spectroscopic examination showed that, besides bismuth and tungsten, the mineral contained only traces of silicon, arsenic, and iron. A sample of the same material had also been given to the British Museum by Mr. E. H. Davison in 1934 and registered provisionally as bismuth tungstate. This, however, would not have provided sufficient of the yellow mineral for chemical analysis. We are also indebted to Mr. Davison for a further generous supply of yellow pellets picked from the wolfram concentrates received since the present work was begun. The mineral has all the attributes of an alteration product probably of native bismuth. It is fine-grained and compact, with hardness $3\frac{1}{2}$, and on fracture it gives a clay-like odour. Some of the pellets show traces of a micaceous mineral and quite frequently enclose native bismuth, wolframite, and bismuthinite. Mr. Russell has picked out from the material he had collected a few green pellets and some showing both the yellow and the green mineral. Spectrographs of the two are identical, but an X-ray powder photograph of the green mineral is quite distinct from that of the yellow mineral. The former still awaits investigation.

An examination of the X-ray powder photograph of the mineral does not reveal the lines characteristic of any of the following compounds: bismuth oxide, cubic bismuth oxide,[1] tungstic oxide, and tungstic acid. Moreover, the photograph appears to be much simpler and to contain fewer lines. The most satisfactory proof that the material is really a single mineral and not a mixture rests upon comparison with the artificially prepared material.

We propose for the mineral the name russellite, in honour of Mr. Arthur Russell, who has contributed much to our knowledge of British mineralogy.

Zambonini has prepared and described two dimorphous forms of normal bismuth tungstate $Bi_2(WO_4)_3$.[2] He obtained a monoclinic form as grey-green to dark green lamellae isomorphous with raspite by direct fusion of the components. This green compound on fusion for three hours at 900–1000° C. with excess sodium chloride was partially converted into the tetragonal modification, as groups of white bipyramidal crystals ($a : c = 1 : 1{\cdot}566$) isomorphous with stolzite ($a : c = 1 : 1{\cdot}5667$), together with thin colourless flakes of bismuth oxychloride. The bismuth oxide content of both forms was determined and agreed very closely with the ideal figure for the normal tungstate.

We repeated these syntheses in the hope that one of the two artificial compounds of Zambonini would prove identical with russellite. No difficulty was experienced in duplicating Zambonini's first preparation. A pale olive-green platy material with a good cleavage resulted which yielded a powder photograph quite distinct from, and much more complex than, that of russellite. It is by no means certain, however, that we have been able to produce Zambonini's white bipyramidal compound. Three separate fusions of the green tungstate with excess sodium chloride at temperatures ranging from 700° to 900° C. all yielded abundantly a flocculent, pale yellow, flaky mass together with a few small grey-white crystal groups which proved to be cristobalite formed by attack on the crucible wall during fusion.

The yellow flaky material gave a powder photograph identical with that of russellite (pl. II, figs. 2 and 3). What is of more importance, the synthesis of this compound enabled us to proceed with the crystal-

[1] M. M. P. Muir and A. Hutchinson, Journ. Chem. Soc. London, 1889, vol. 55, p. 143. The X-ray photographs obtained from this substance indicate that it is a definite compound, quite distinct from ordinary Bi_2O_3.

[2] F. Zambonini, Gazzetta Chimica Italiana, 1920, vol. 50, pt. 2, pp. 129 and 132.

[M.A. 2–245.]

graphic and optical studies of single crystals, for under the microscope
e artificial compound is seen to consist of minute thin laths up to 0·25
m. long (positive elongation) and thin plates yielding no optic picture.
he refractive index of the crystals (obtained in sulphur-selenium melts)
2·2. A few laths were mounted for X-ray work and rotation photo-
aphs were taken about the principal axes (pl. II, fig. 1). These showed
at the mineral is tetragonal with unit cell edges, a 5·42±0·03 Å.,
11·3±0·3 Å. The laths are elongated along the c-axis and the plane of
e lath is (100) or (110). Moreover, the single crystal photographs were
actly superposable upon powder photographs of russellite and of the
tificial compound, so that there is good reason to suppose that the
tter is a single mineral and not a mixture. The axial ratio of the yellow
mpound obtained from the unit cell measurements is $a : c = 1:2{\cdot}084$,
nd is markedly lower than the value for stolzite $a : c = 1:2{\cdot}208$. Divid-
g these values by $\sqrt{2}$, in order to compare them with the axial ratios
dopted by Dana, yields 1·476 and 1·561 respectively. It is to be noted
at the value 1·476 is well below the value observed by Zambonini for
s crystals of tetragonal bismuth tungstate.

Since the natural and artificial compounds give identical X-ray
notographs, they must have essentially the same structure and it was
tonishing to find, on chemical analysis, that the natural mineral has a
mposition approximating to $Bi_2O_3.WO_3$, while the artificial approxi-
ates to $Bi_2O_3.2WO_3$ (in both cases, the departure from these formulae
outside the probable analytical error). Further, when the specific
avities were determined, it was found that that of the artificial mineral
as greater than that of the natural, contrary to what would be expected
om their compositions. The most natural assumption was that the
ecimens had somehow got interchanged, and therefore new analyses
nd specific gravity determinations were made on fresh material, and
duplicate; the first results were thus confirmed, and it was evident
at we were dealing with a very remarkable substance. It was also
und that the natural material varies somewhat in composition, while
fferent batches of the artificial material also show considerable
ariations.

The chemical analyses, unit cell dimensions, densities, and atoms per
nit-cell in natural and artificial russellite are given in table I. The
nalyses were made on a semi-micro scale, using 0·1 gm. of material, by
ie following method, while the densities were determined with the
icro-pyknometer.[1]

[1] F. A. Bannister and M. H. Hey, Min. Mag., 1938, vol. 25, p. 30.

TABLE I. Chemical and physical data for russellite and artificial $(Bi_2,W)O_3$.

		Natural mineral.		Artificial product.		
Percentage composition	Bi_2O_3	68·26	62·3	48·15	50·3	42·3
	WO_3	25·50*	32·1	45·85	43·0	51·8
	As_2O_3†	0·26	0·29	—	—	—
	Fe_2O_3	trace	n.d.	—	—	—
	Al_2O_3	—	—	2·26	n.d.	n.d.
	Insoluble	1·60	1·6	1·78	1·8	n.d.
	Loss on ignition ...	4·86	n.d.	1·78	n.d.	n.d.
	Total	100·48	—	99·82	—	—
	Oxygen	13·13	13·9	15·37	15·1	16·0
Atoms per unit cell	Bi	4·60	4·2	3·56	3·75	3·1
	W	1·72	2·2	3·41	3·2	3·85
	As	0·04	0·04	—	—	—
	O	12·14	12·8	15·58	15·3	16·2

Specific gravities D_4^{21}, corrected to vacuum: Natural mineral: 7·26, 7·54, 7·18, 7·43; mean 7·35±0·2. Artificial: 8·12, 8·01, 8·14, 7·97; mean 8·06±0·1.

Unit cell dimensions for both natural and artificial material: a 5·42±0·03 Å., c 11·3±0·3 Å.

The mineral powder was ignited just below a red heat, the loss on ignition being noted, then evaporated to dryness twice with strong hydrochloric acid, extracted with dilute acid, and filtered with an Emich filter-stick; the residue was extracted with ammonia and filtered; any residue after this was again extracted with hydrochloric acid and ammonia, then ignited and weighed. The united acid solutions were precipitated with H_2S after addition of a little tartaric acid and the precipitate collected on paper and dissolved in nitric acid, the paper being ignited and the small residue extracted with nitric acid; in the united nitric acid solutions, bismuth was precipitated as basic carbonate. The acid filtrate was boiled free from H_2S and a little tungstic acid recovered from it by precipitation with tannin and cinchonine, this precipitate being carefully ignited in a crucible, in which the ammoniacal extracts containing the bulk of the tungstic acid were then evaporated down and ignited. Iron (in the natural material) or aluminium (in the artificial) was recovered from the filtrate from the tannin-cinchonine precipitate by addition of ammonia. Arsenic in the natural material was determined on a separate portion of 0·1 gm. by distillation as $AsBr_3$, followed by precipitation and weighing as As_2S_3.

The insoluble material and alumina in the analyses of the artificial compound are evidently derived from the crucible, but it was not clear whether the very considerable water content in both the natural and artificial material should be included as an essential constituent of the compound, or excluded as adsorbed moisture. An X-ray powder photo-

* A third partial analysis of the natural mineral gave WO_3 23·44 per cent. All the analyses were made on separate specimens or preparations.

† Total arsenic as As_2O_3; the state of oxidation was not determined.

aph of material which had been gently ignited was found to be identical th that of the untreated material, and it is therefore probable that e water is adsorbed; in the following discussion it has been assumed at the water is wholly adsorbed.[1]

The chemical and physical data thus show that natural and artificial ssellite have quite different numbers of oxygen atoms per unit cell; t they give identical X-ray powder photographs. This is, of course, ssible provided the metal atoms are similarly placed in the structures the two substances, since the contribution of the oxygen atoms to the tensities of the diffractions is very small compared to that of the metal oms. But it was clear that for a better understanding of the relation the two compounds, a knowledge of their crystal-structures was sirable.

A rotation photograph of the artificial compound was readily indexed, d formed the basis for indexing the powder photographs. The served diffractions clearly indicated that the heavy bismuth and tung- en atoms, considered alone, must satisfy the symmetry of the tetra- nal space-group D_{4h}^{19}, at least to a very close approximation, but since e light oxygen atoms would contribute very little to the observed ffractions, the true symmetry might be lower. No indication could found to suggest that the unit cell chosen was a submultiple of the ic cell, as the atomic cell contents might suggest.

Moreover, the observed diffractions clearly showed that there was a ry marked pseudo-cell having half the height of the true cell; this eudo-cell has approximately cubic dimensions. After a careful con- deration of a variety of possible arrangements, we concluded that the avy atoms (bismuth and tungsten) must lie approximately on a ce-centred pseudo-cubic lattice conforming strictly or very closely the symmetry requirements of the space-group D_{4h}^{19}; and that was impossible to find separate sets of equivalent lattice positions r the bismuth and tungsten atoms, which must be distributed over e eightfold set of equivalent positions, part of which will then vacant.

The only possible position for the bismuth and tungsten atoms is thus e uniparametral eightfold position of D_{4h}^{19}, $\Sigma_8 00u$; a comparison of ensities in the first to fifth layer-lines of a rotation photograph of a ystal of the artificial material about the *c*-axis (table II) fixes

[1] This is not proved, at least for the natural mineral; a large part of the water ght be present as 'zeolitic' water of crystallization in the vacant spaces of the ucture, and its expulsion would not appreciably affect the X-ray photographs.

the parameter u at $0{\cdot}23 \pm 0{\cdot}005$, and this result is confirmed by a comparison of observed and computed intensities in a powder photograph (fig. 1). This arrangement holds for both the natural and the artificial compound.

TABLE II. Observed and computed intensities of the diffractions on an X-ray rotation photograph of artificial $(Bi_2,W)O_3$ about the axis [001].

ξ.	Indices.	Intensities. Obs.	Calc.
Equator:			
0·58	(200)	*vs*	10
0·82	(220)	*s*	8
1·16	(400)	*s*	4
1·29	(420)	*s*	6
1·63	(440)	*w*	3·4
1·73	(600)	*m*	3·6
1·82	(620)	*m*	10
First layer-line:			
0·29	(101)	*vw*	0·8
0·65	(211)	*vw*	0·4
0·87	(301)	*vvw*	0·2
1·04	(321)	*vvw*	0·2
1·19	(411)	*vvw*	0·2
1·45	(431) (501)	—	0·2
1·56	(521)	—	0·1
1·76	(611)	*	0·2
1·85	(541)	*	0·2
1·94	(631)	*	0·4
Second layer-line:			
0·40	(112)	*vs*	23
0·92	(312)	*s*	16
1·23	(332)	*m*	6
1·46	(512)	*s*	10
1·68	(532)	*s*	12
Third layer-line:			
0·29	(103)	*vvw*	1·5
0·65	(213)	*vvw*	1·5
0·86	(303)	*vvw*	0·5
1·04	(323)	*vvw*	0·9
1·19	(413)	*vvw*	0·7
1·45	(433) (503)	—	0·9
1·56	(523)	—	0·7
1·76	(613)	*	0·9
1·85	(543)	*	1·3
1·94	(633)	*	2
Fourth layer-line:			
0·58	(204)	*vs*	12
0·82	(224)	*m*	6
1·16	(404)	*m*	5
1·29	(424)	*m*	10
1·63	(444)	*m*	5
1·74	(604)	*m*	8
1·82	(624)	*s*	23
Fifth layer-line:			
0·29	(105)	*w*	3

ξ the longitudinal cylindrical co-ordinates of diffraction spots, see J. D. Bernal, Proc. Roy. Soc. London, Ser. A, 1926, vol. 113, p. 117. [M.A. 3–333.]

* General fog would probably prevent observation of this diffraction.

The oxygen atoms are unfortunately too light to fix by intensity considerations. In the artificial compound, they number sixteen, and if they are all equivalent (as seems most probable), they must occupy the positions[1] $\Sigma_{16} v\ \frac{1}{4}\ \frac{1}{8}$ of D_{4h}^{19} with v between 0·27 and 0·29. A value of 0·29 for v makes each oxygen equidistant from four bismuth or tungsten

[1] If it is assumed that the symmetry is lower than D_{4h}, the range of possible positions of the oxygen atoms is little affected. The more symmetrical assumption is made here as there is no evidence against it.

oms at 2·40 Å., each bismuth or tungsten being surrounded by eight ygen at the corners of a distorted cube. With a value[1] of 0·27 for v, ch oxygen has as neighbours two bismuth atoms at 2·32 Å. (located at u and $0,\frac{1}{2},\frac{1}{4}-u$ for the oxygen at $v\ \frac{1}{4}\ \frac{1}{8}$) and two at 2·55 Å., and each

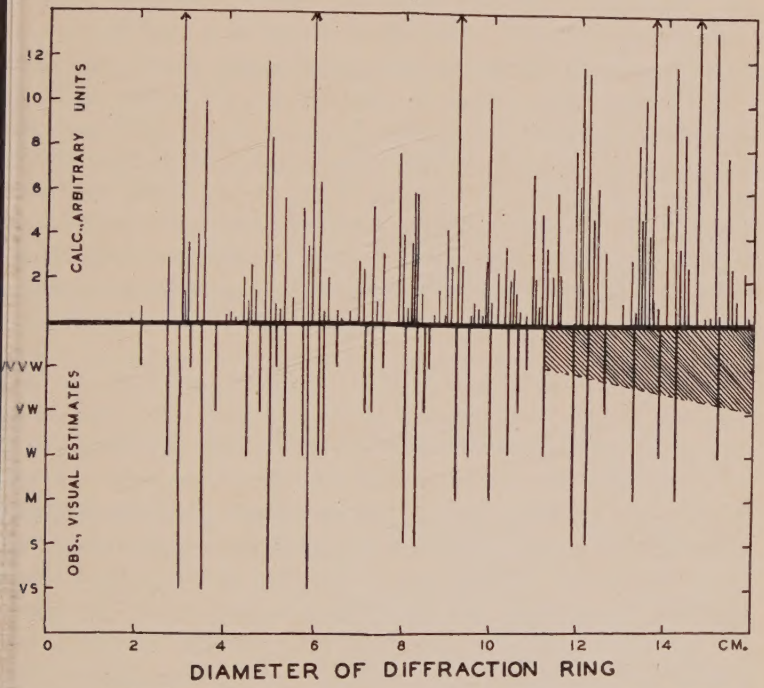


FIG. 1. Observed and calculated intensities of the diffractions in a powder otograph of russellite, taken with unfiltered Cu radiation λ 1·539 Å., in a indrical camera, diameter 6·04 cm. The film showed considerable background from 11 cm. outwards (represented by shading in the figure), which may obscure ak lines.

muth atom has as its nearest neighbours four oxygen atoms distant 2 Å. and located at the corners of a rectangle in a plane parallel to 01), a structure which seems less probable than the more symmetrical e with $v = 0{\cdot}29$.

For the natural mineral, russellite, there are two structural possi-ities. It may be strictly isomorphous with the artificial compound and

[1] Values of v less than 0·27 have been rejected since they would lead to bismuth-gen distances less than 2·32 Å., which is the distance found in the oxyhalides of nuth (F. A. Bannister, Min. Mag., 1935, vol. 24, p. 53).

have an incompletely filled set of oxygen positions, or the structure may be different, the oxygen being divided between an eightfold and a fourfold lattice position. In the second case, it is not possible to find positions in accordance with the symmetry of the space-group D_{4h}^{19} which would give reasonable interatomic distances. But in the space-group D_{2d}^{12} (derivable from D_{4h}^{19} by a reduction of symmetry) an eightfold position $\Sigma_8 00u$ is available for the bismuth and tungsten atoms, while if the twelve oxygen atoms occupy the fourfold special position $\Sigma_4 000$ and the eightfold uniparametral position $\Sigma_8 \frac{1}{4}\, v\, \frac{1}{8}$ with $v = 0{\cdot}345$, reasonable interatomic distances are obtained. Each bismuth or tungsten atom has as nearest neighbours three oxygen atoms, two at 2·29 Å. and one at 2·60 Å., while two more oxygens lie 2·68 Å. distant; the nearest approach between the oxygen atoms is 2·71 Å. (from the oxygen at 000 to that at $\frac{1}{4}\, v\, \frac{1}{8}$). The bismuth or tungsten atom and its three neighbouring oxygen atoms are coplanar. It is difficult to say which of these structures is the more probable.

Russellite and the related artificial compound have unit cells of the same size as those of the scheelite group, and the X-ray photographs of both groups are very similar, the most notable difference being that the odd layer-lines of a *c*-axis rotation photograph are relatively much stronger with russellite than with stolzite (which has atoms of comparable scattering powers). For russellite, which has only 12 oxygen atoms per unit cell, the scheelite type of structure would naturally be impossible.[1] It is possible that the artificial material might have a scheelite structure, the bismuth and tungsten occupying separate fourfold positions, which would not be wholly filled; but such a structure would contain a proportion of groups of four oxygen atoms without a central metal atom and does not, therefore, seem at all likely. It is unfortunate that owing to the low diffracting power of the oxygen atoms they cannot be directly located and the structure definitely fixed.

In the structures adopted, bismuth and tungsten are equivalent, and there is no sign of the WO_4 group of the tungstates; the natural assumption that russellite, being nearly $Bi_2O_3.WO_3$, must be basic bismuth tungstate $(BiO)_2WO_4$ is therefore quite incorrect, and so far from being a tungstate at all, russellite is an oxide, a mixed crystal of Bi_2O_3 and WO_3, crystallizing in a form quite different from that of either of the

[1] If 16 oxygen atoms per unit cell were asumed for russellite, the specific gravity should be 9·8, which differs from the experimental value by far more than the probable experimental error.

ıre oxides,[1] and its empirical formula must be written $(Bi_2,W)O_3$. Whether the artificial material really represents the same species as ssellite, or whether it is to be regarded as a compound of different ut closely allied) structure remains uncertain.

Summary

Russellite, a new species, occurs at the Castle-an-Dinas wolfram mine, . Columb Major, Cornwall, as pale yellow fragments. It is tetragonal, ace-group D_{2d}^{12} or possibly D_{4h}^{19}, a 5·42±0·03 Å., c 11·3±0·3 Å., repeat $Bi,W)_{8-n}O_{12}$. Its composition is near $Bi_2O_3.WO_3$, but it is an isomorphous ixture of oxides, not a bismuth tungstate. The crystal-structure has een studied, and the bismuth and tungsten atoms located. The number nd position of the oxygen atoms is discussed, and two possibilities escribed. An artificial compound with a composition near $Bi_2O_3.2WO_3$ nd a repeat $(Bi,W)_{8-n}O_{16}$ is either a member of the same isomorphous ries or has a structure very closely allied to that of russellite.

The occurrence and associations of russellite.

By Arthur Russell.

Towards the end of March, 1934, during one of my periodic visits to ıe Castle-an-Dinas wolfram mine, St. Columb Major, Cornwall (six-ch ordnance map, 33 SW.) my attention was called by Mr. J. Chy-weth (the manager) and Mr. W. A. Kessell (the underground agent) a pale yellow, heavy mineral which had commenced to appear along ith the wolframite in the jig concentrates in the mill. As the wolfram re had, up to that time, been remarkably free from any other heavy inerals, with the exception of a little cassiterite, the mineral at once ccited my interest, and having determined the presence of bismuth and ngsten, I again visited the mine and with Mr. Kessell made a careful arch in the particular stope between no. 1 and no. 2 level in the dimentary rock from which the wolfram ore containing the mineral as undoubtedly then coming. No trace of it, however, rewarded our arch. Since then the mineral has only appeared in the concentrates at ng intervals and in diminishing quantities, obviously owing to the fact at it occurs only in one limited section of the vein. Repeated and very reful searches by both Mr. Kessell and myself have up to now failed

[1] It was thought at first that cubic Bi_2O_3 might be an end-member of the series, t comparison of the X-ray photographs disproves this. It is not unknown for a ixed crystal to have a structure unstable in either of the pure components.

to detect a single specimen of the mineral, either in situ or in the crude ore. This, however, can be explained by the fact that it is probably present in small masses only, and owing to its inconspicuous colour and structure it would be exceedingly difficult to see underground, while the dirt-covered ore is tipped direct from the level mouth into the mill.

In the 'Mining Magazine' (London) for May, 1934, the Cornish correspondent referred to the mineral as being bismuth tungstate, and suggested that it might probably be a new mineral. This statement was apparently due to the fact that Mr. H. W. Hutchin, assayer of Tuckingmill, to whom a sample of the concentrate had been submitted, had detected bismuth and tungsten, and very naturally assumed the mineral to be a bismuth tungstate. Since that date Dr. M. H. Hey and Mr. F. A. Bannister, have, at my instigation, kindly undertaken the chemical analysis and the determination of its X-ray structure, with the result that the mineral proves to be undoubtedly a new species, and an interesting addition to the long list of minerals occurring in that most wonderful store-house—Cornwall.

The cream-coloured to greenish pellets of russellite show the following intimately associated minerals, all of which are sometimes embedded in their mass: native bismuth, wolframite, limonite, quartz, topaz, lithia-mica, and black prisms of tourmaline.

The main geological features of the mine have been described by Mr. E. H. Davison in 1920[1] and also by myself in 1924,[2] and are as follows. The hill of Castle-an-Dinas, crowned by an ancient camp, rises to a height of 702 feet, and is a small granite boss or outlier rising through banded sediments belonging to the Meadfoot series. The granite outcrops as a small rudely elliptical area on part of the summit and western side, the remainder of the hill consisting of the altered sediments. Small veins containing cassiterite have in the past been worked in the sediments near the north-east base of the hill, while on the south-west the original Castle-an-Dinas mine worked a stanniferous elvan by open quarries. In 1917, in consequence of somewhat rounded masses of wolframite having been found in trial pits sunk on the north side, mining operations on a small scale were commenced by the late Mr. W. E. Cox

[1] E. H. Davison, On the geology of Castle-an-Dinas and Belowda Beacon. Trans. Roy. Geol. Soc. Cornwall, 1919, vol. 15, pp. 269–285. On the geology of Castle-an-Dinas wolfram mine. Geol. Mag. London, 1920, vol. 57, pp. 347–351. [M.A. **1**–387.]

[2] A. Russell, Topaz from Cornwall, with an account of its localities. Min. Mag., 1924, vol. 20, pp. 231–233.

of Newquay, the mine in 1918 being taken over by the South Crofty Company, by whom it has since been worked whenever the price of wolfram has justified it.

The wolfram lode has a direction of about 18° east of north, is nearly vertical, and varies in width from 2 to 6 feet. It is worked by means of four levels and a shaft, all on the north side of the hill, and traverses the sedimentary rock, entering the granite mass, or tongues connected with it, as the centre of the hill is approached. The sediment near the surface is a pinkish baked slate, in depth passing into a brownish, finely laminated gritty rock, showing marked zigzag puckering. The granite is white, fine-grained, and sometimes contains tourmaline, and near the lode is somewhat kaolinized and often passes into greisen. Quite recently, in no. 3 level, a soft gilbertite-bearing china-stone with deep-violet fluorite upon its joints has been driven through near the centre of the hill. The lode filling, while traversing the sediment, consists of quartz with limonite coatings, wolframite, topaz, brown lithia-mica, and some tourmaline, the rarer minerals present being cassiterite, native bismuth, bismuthinite, russellite, arsenopyrite, scorodite, wavellite, turquoise, and, very rarely, native copper and cuprite. Practically the whole of the wolfram so far produced has come from the sedimentary section of the lode. On entering the granite, arsenopyrite has, unfortunately, recently made its appearance in quantity; the concentrates from that particular section containing about half and half of the two minerals. Recently the lode in no. 3 level completely cut out against what appears to be the main granite core, but on driving 438 feet through the mass, it has again been found in the sediment, highly productive of wolfram on the south side of the hill. The lode has also been picked up by trenching on the south side of the hill, and new life has thus been given to the mine. The following minerals have been found in the lode.

Wolframite forms large, bright iron-black lamellar masses easily parting along the lamellae, which are often coated with a thin film of quartz, the outside of the masses being usually coated with limonite. The lamellae are elongated in the direction of the *c*-axis and are fluted from repeated oscillations of *a* (100) and *m* (110) and have a perfect *b* (010) cleavage. Terminated crystals, always rare in Cornwall, have so far not been observed. A curious development of this mineral, peculiar, I believe, to the locality, consists of masses built up of narrow alternating and rudely parallel strings of wolframite and quartz or quartz with topaz, between which are films of white pearly mica, twenty or so of these to an inch, giving the specimens a peculiar striped appearance.

These little wolframite strings often have a blue, green, or bronze iridescence and are formed of small parallel crystal lamellae with the *c*-axis usually at right angles to the string though sometimes set diagonally. Each individual is continuous throughout the mass though intersected and sometimes slightly faulted by the quartz strings, and when faulted all are slightly shifted in the same direction, the amount of displacement appearing to be dependent on the width of the quartz string. In one specimen the strings, instead of being straight, are distinctly folded. Associated with these masses are ordinary vein quartz, scales of rusty lithia-mica, and rarely a little turquoise. Some of the large lamellar masses of wolframite are the finest examples of the mineral which have been met with in Cornwall.

Cassiterite is rarely visible though at times the wolfram concentrates have contained up to 3% of the mineral. In 1936, a few specimens were found in the granite section of the mine which show numerous small, translucent, yellowish-brown, acute pyramidal crystals up to 6 mm. in length, embedded in quartz with needles of black tourmaline and interstices filled with white kaolin. A crystal was measured, the forms present being *m* (110), *e* (101), *s* (111), *z* (321) [Dana's letters].

Arsenopyrite, as already stated, has only recently (1937) made its appearance in the deeper granitic section of the mine. It occurs as large silver-white masses in quartz, and also in striped masses consisting of alternating parallel strings of arsenopyrite and quartz, exactly resembling the specimens described under wolframite.

Native copper and cuprite.—Both these minerals are of very rare occurrence. A specimen which I found on the dump derived from the upper part of the lode in the sediment shows small bright leaves and octahedra of native copper associated with minute bright octahedra of cuprite in quartz with topaz, wavellite, and scorodite. Small pellets up to 8 mm. of native copper have also occasionally been observed among the wolfram concentrates.

Native bismuth and bismuthinite.—Small quantities of native bismuth were found by myself in 1934 along with the russellite amongst the wolfram concentrates from the jigs. Like the russellite, all efforts have so far failed to detect a single specimen in situ or in the crude ore. It occurs in the sedimentary rock section of the mine and is of much rarer occurrence than the russellite with which it is associated. The fragments of native bismuth as they come from the jigs attain a maximum size of about 1 cm. and from the unbroken appearance of some of them it may be assumed that this is about the maximum size that they

ecurred in the vein stuff. Some of the fragments consist of native bis-
nuth only with the characteristic reddish silver-white colour and coarse
ımellar cleavages parallel to (0001) and (02$\bar{2}$1); others are pellets of
ntive bismuth externally covered with grey bismuthinite; others, again,
onsist of pellets of the yellow to greenish russellite with a core of native
ismuth. Occasionally the native bismuth has a bluish iridescent film.
he directly associated minerals are quartz, topaz, muscovite, and
olframite.

Bismuth minerals have been long ago recorded from four other
calities in this neighbourhood:

Trethurgey, St. Columb Major.—The MS. catalogue of the Philip Rashleigh collec-
on contains an entry under bismuth: 'No. 1 Native Bismuth from Tresurgy [later
ered in Rashleigh's handwriting to Trethurgey] near St. Columb.' The name
rethurgey is no longer to be found on the six-inch ordnance map, but in the map
ppended to William Borlase's 'Natural History of Cornwall' (1758), and on Thomas
artyn's map of Cornwall (1784), a place Trethergy is shown in a position close to,
d probably identical with Ennisworgey, one mile south-west of Castle-an-Dinas.
ne actual specimen to which the entry refers is probably in Truro Museum,
t is inaccessible. William Phillips in his 'Mineralogy' (second edition, 1819,
205), says 'carbonate of bismuth is said to have occurred at Tregurthy and
. Columb'.

St. Wenn.—The collections belonging to the Royal Geological Society of Cornwall,
nzance, and the Royal Institution of Cornwall, Truro, both contain specimens
sisting of small rolled pellets up to 1 cm. of bismuthinite (confirmed by myself)
sociated with quartz and a little gilbertite, labelled St. Wenn. It is almost cer-
nly this occurrence which is referred to by Thomas Hogg in his 'Manual of
ineralogy' (Truro, 1825, p. 26), in which it is stated that 'sulphuret of bismuth . . .
eurs in a stream-work in the parish of St. Columb, of a dark lead grey colour, in the
ate of water worn pebbles'. The actual locality was very probably the alluvial
ley directly north of Castle-an-Dinas, which divides the parishes of St. Columb
ajor and St. Wenn, and which has, in the past, been extensively streamed for tin,
d which, in addition, contained wolframite, all three minerals having very likely
me from the Castle-an-Dinas lode outcrops.

Trugo mine, St. Columb Major (six-inch ordnance map 40 NE.) situated on the
ad between White Cross and Trebudannon. According to Thomas Hogg ('Manual
Mineralogy', Truro, 1825, p. 24) native bismuth accompanied the smaltite which
curred in a small vein 4 to 6 inches wide crossing the copper lode in this mine,
hich is in greenstone. (See also W. Pryce, 'Mineralogia Cornubiensis', 1778, p. 50.)
o specimens of native bismuth from this locality appear to have been preserved.

Cost All Lost tin mine, later known as *Roche Rock* or *Cornubia mine, Roche* (six-
ch ordnance map, 41 NE.). Thomas Hogg ('Manual of Mineralogy', Truro, 1825.
25) describes under carbonate of bismuth, a greyish-green, brownish, and
llowish-grey mineral with small patches of included quartz which effervesces
nitric acid, as having been found by Mr. John Michell at this mine, which is
slate and granite. Unfortunately no specimens from this locality appear
have been preserved, for it would be interesting to know what this mineral
lly was.

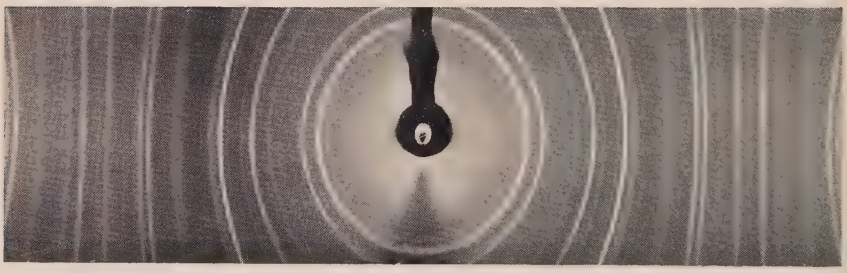
Scorodite occurs as pale greenish-grey minutely botryoidal crusts on cellular masses of quartz with radiating spheres of wavellite which it also invests. On other specimens it occurs with wavellite as a greyish-green coating on the banded sediment. The mineral was evidently formed by the alteration of arsenopyrite and occurred in the upper part of the lode.

Wavellite occurs as flat, white to slightly greenish radiating disks up to 2 cm. in diameter, along with a greyish-green coating of scorodite on the joints of the laminated sediment traversed by quartz veins containing wolframite, topaz, &c., also more rarely as complete white spherical aggregates up to $1\frac{1}{2}$ cm. in diameter in cavities in quartz lined with scorodite. Recently I have obtained a large mass which on being broken up is seen to consist almost entirely of small, radiating spheres and botryoidal crusts of wavellite externally varying in colour from white, green, yellow, or rusty brown, and internally from white to grey. In many of the cavities the spheres of wavellite are covered with minute crystalline botryoidal aggregates of bright green turquoise, a good deal of which is present throughout the mass. Some of the spheres are built up of concentric layers, others, which are very beautiful under the microscope, consist of bristling aggregates of minute acicular crystals, these sometimes studding botryoidal aggregates of turquoise. The wavellite crystals are elongated in the direction of the *c*-axis and show the forms *b* (010), *m* (110), *p* (101) [Dana's letters]. The (110) faces are deeply striated vertically and are not measurable. In the groundmass, included in the spheres of wavellite, are small black prisms of tourmaline; the other minerals present being quartz, rusty yellow ochre, and scales of lithia-mica; the whole forming a most curious assemblage of minerals. Wavellite has hitherto been found only at one other locality in Cornwall, namely, Stenna Gwyn mine, St. Stephen-in-Brannel.

Turquoise occurs as a bluish-green or leaf-green (Ridgway) minutely crystalline botryoidal and sometimes rippled crust on the banded sediment. Also as light bluish-green to rarely true turquoise-blue, minutely crystalline porous masses with wavellite, yellowish-brown lithia-mica, tourmaline, and limonite. A full description of the mineral will appear in a subsequent number of this Magazine.

Lithia-mica.—The surfaces of the masses of wolframite are frequently coated with rusty brown scales and rosettes of six-sided platy crystals of a lithia-mica almost certainly referable to zinnwaldite. A fine specimen, in which the crystals making up the rosettes attain a diameter of 8 mm., was recently (February, 1938) obtained by myself from the extreme south end of the mine where the lode re-enters the sediment.

1



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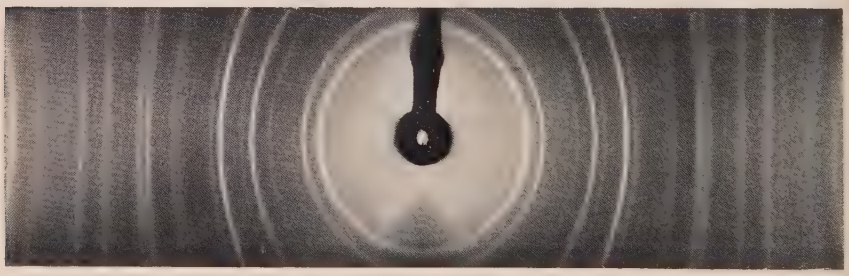

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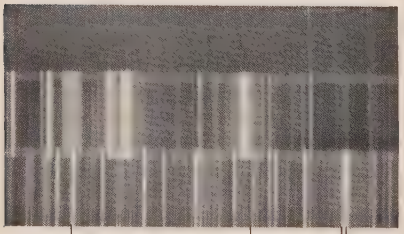

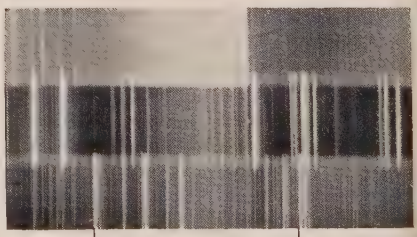

4

M. H. HEY and F. A. BANNISTER: RUSSELLITE

Topaz, in places, forms an important constituent of the lode, and its occurrence has been fully described by myself in this Magazine in 1924. In the stope from which the russellite came, topaz formed a considerable portion of the lode filling. It occurred in a rusty yellowish friable coarsely crystalline form associated with quartz, wolframite, lithia-mica, tourmaline, and a little turquoise, and occasionally showed distinct crystals.

Psilomelane has recently been found in small quantity as a botryoidal crust on the quartzose vein-stuff.

Having eagerly watched with increasing interest the Castle-an-Dinas mine from its commencement some twenty-one years ago, I must here express my thanks to Mr. Clarence V. Paull for permission to visit the property, and my especial gratitude to Mr. J. Chynoweth and Mr. W. A. Kessell for their unfailing help and many acts of kindness.

Explanation of Plate II.

X-ray and spectrographic photographs of russellite.

Fig. 1. Single crystal of artificial $(Bi_2,W)O_3$ rotated about *c*[001] axis.

Fig. 2. Powder photograph of russellite.

Fig. 3. Powder photograph of artificial $(Bi_2,W)O_3$.

All three X-ray photographs were taken with unfiltered Cu radiation λ 1·539 Å. in a cylindrical camera, diameter 6·04 cm. A length of 10 cm. on the original films is equivalent to 9 cm. on the reproduced figures.

Fig. 4. Part of spectrographic record of (top) graphite electrodes, (centre) R.U. powder, (bottom) russellite.

R.U. powder is composed of a base of Mg, Ca, and Zn oxides and small, varying amounts of 51 elements in such proportions that only a few of the most sensitive lines (raies ultimes) appear in the emission spectra. The wave-lengths of the marked lines are As 2790, As 2860, As 2898, Bi 2899, W 4009, W 4295.

The composition and paragenesis of the hornblendes of the Glen Tilt complex, Perthshire.

By W. A. Deer, M.Sc., Ph.D.

Department of Geology, University of Manchester.

[Read November 4, 1937.]

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I. *Introduction.*

THE south-eastern margin of the Glen Tilt complex[1] consists of a long strip of diorites with a number of small associated patches of rocks of appinitic type. Xenoliths, both of hornblendite and hornblende-schist, the latter belonging to the Perthshire series of the Dalradian, are found enclosed within the dioritic rocks, which range petrographically from diorite to quartz-mica-diorite. In all these rocks hornblende is the most important ferromagnesian constituent always predominating over pyroxene in the basic members and frequently persisting to the exclusion of biotite in the intermediate rocks of the intrusion. The hornblendes were examined chemically because of the difficulty of estimating their composition even from a thorough optical investigation. As they play such an important role in the complex it is considered that they may give some indication of the history and mode of formation of the rocks in which they occur. Such a chemical investigation of a series of related hornblendes will also indicate the possible range of composition of common amphiboles within the diorites and related rocks of a single complex.

Nine complete analyses of the hornblendes have been made, five from the appinites and diorites, one from a hornblendite xenolith, one from a

[1] The geology of Upper Strathspey, Gaich and the Forest of Atholl. Mem. Geol. Surv. Scotland, Sheet 64, 1913.

hornblende-schist xenolith, one from an injected hornblende-schist, and finally one from unaltered hornblende-schists of the Perthshire series.

Although a number of methods were tried in the separation of the hornblendes from the rest of the rock constituents, the following procedure was found to be the most efficient. In the case of the larger hornblendes from the appinites, and injected and xenolithic hornblende-schists, in which the crystals measured at least 0·25 by 0·25 cm. (analyses 2, 4, 8, 9), they were first drilled as cleanly as possible from the other rock constituents using a dental drill. This provided a highly concentrated fraction before crushing for the separation of included impurities and small adhering particles. All iron-ore was then removed from the crushed material by an electromagnetic separator and practically all the quartz and felspar by repeated fractional separations in bromoform. The heavier impurities, such as occasional grains of pyroxene and sphene were removed by continuous separation in methylene iodide. Finally, by adjusting a solution of methylene iodide and benzene until its specific gravity was just greater than that of the hornblende, and then just less than the hornblende, most of the composite grains were removed. In the case of the smaller hornblendes (analyses 1, 3, 5, 6, 7) the whole rock was crushed and many more separations were required to obtain a pure concentrate. In both groups, however, this fraction was never completely free from a number of composite grains. The most satisfactory method of removing the latter was to pick these unwanted grains out with a camel-hair brush under a biological dissecting or low-powered binocular microscope, and each grain was examined separately before being finally passed for analysis. The analyses were made on fractions weighing between 1·5 and 2·5 grams according to the difficulty or ease of obtaining a pure concentrate. This depended almost entirely on the grain-size required to obtain the maximum number of monomineralic grains, which varied from 0·25 to 0·50 mm. according to the texture of the rock in which the hornblende occurred.

II. *The Hornblende Analyses.*

The analyses of the hornblendes are given in table I together with their optical properties and specific gravity. The values for $2V$ and $\gamma:c$ were measured on the universal stage, and the specific gravity was obtained by matching small grains with methylene iodide diluted with benzene and measuring the specific gravity of the liquid with a hydrostatic balance.

TABLE I. Analysis of hornblendes. (Analyst W. A. Deer.)

	1.	2.	3.	4.	5.	6.	7.	8.	9.
SiO_2	42·11	43·01	48·92	45·50	48·32	48·96	44·23	44·15	47·14
TiO_2 ...	2·76	2·87	1·21	1·73	1·43	1·07	1·81	3·73	1·74
Al_2O_3 ...	10·05	12·01	5·88	9·66	6·43	7·85	14·62	10·59	9·44
Fe_2O_3 ...	2·82	3·35	6·50	6·06	5·45	3·62	5·11	5·02	3·66
FeO	15·14	9·07	7·79	6·90	7·90	8·25	8·94	8·89	8·38
MnO ...	0·24	0·19	0·17	0·18	0·13	0·12	0·21	0·17	0·11
MgO ...	11·48	14·00	14·32	14·61	14·82	15·69	10·78	12·30	14·44
CaO ...	11·34	11·79	11·37	11·24	11·99	11·90	10·81	11·80	10·53
Na_2O ...	1·01	1·08	1·20	1·20	0·99	1·04	1·51	1·26	1·15
K_2O	1·43	1·01	0·71	0·92	0·67	0·53	0·61	1·10	1·30
$H_2O+105°$ ...	2·02	1·40	1·37	1·73	1·61	0·63	1·42	0·95	2·00
$H_2O-105°$ ...	0·06	0·06	0·18	0·19	0·06	0·08	0·08	0·11	0·53
F	—	0·84	0·27	trace	trace	1·41	0·22	0·84	—
	100·46	100·68	99·89	99·92	99·80	101·15	100·35	100·91	100·42
Less O for F...	—	0·36	0·11	—	—	0·61	0·09	0·36	—
	100·46	100·32	99·78	99·92	99·80	100·54	100·26	100·55	100·42
Sp. gr. ...	3·205	3·170	3·159	3·164	3·159	3·160	3·174	3·176	3·162
$2V$	66°	70°	78°	77°	76°	75°	70°	71°	74°
$\gamma:c$	15°	15°	19°	18°	20°	19°	18°	17°	18°
α	1·662	1·650	1·643	1·651	1·653	1·651	1·659	1·654	1·651
β	1·673	1·664	1·655	1·660	1·663	1·662	1·670	1·665	1·661
γ	1·680	1·672	1·664	1·669	1·671	1·670	1·677	1·673	1·669
$\gamma-\beta$ ...	0·007	0·008	0·009	0·009	0·008	0·008	0·007	0·008	0·008
$\gamma-\alpha$ ...	0·018	0·022	0·021	0·018	0·018	0·019	0·018	0·019	0·018

Hornblende from:	Pleochroism. α	β	γ
1. Typical Glen Tilt diorite ...	pale yellow-green	greenish-yellow	brownish-green
2. Coarse appinite (large phenocrysts)	pale yellow-brown	brown-yellow	dark yellow-brown
3. Coarse appinite (small) ...	straw	yellow-green	green
4. Pyroxene-bearing appinite	pale yellow-brown	light yellow-brown	brownish-yellow
5. Quartz-orthoclase-plagioclase-hornblende-rock ...	yellow-green	pale brown	brown
6. Hornblendite xenolith ...	straw	yellow-green	brownish-green
7. Hornblende-schist ...	pale yellow-green	pale green	green
8. Injected hornblende-schist	pale brown	brown	dark brown
9. Hornblende-schist xenolith	pale brown	brown	dark brown

The hornblende from the typical Glen Tilt diorite shows the greatest amount of individuality both chemically and optically. It is distinguished from the hornblendes of the appinites by a very high percentage of ferrous iron and an extremely low Fe_2O_3/FeO ratio, and this high iron content is shown by the high specific gravity. Furthermore, it is the only hornblende that combines low silica with a moderately low alumina percentage, and finally the Na_2O/K_2O ratio is very much less than in the other varieties. This distinct chemical constitution has resulted in the refractive indices being higher than those of the other hornblendes of the complex. This hornblende has been consistently developed in all the diorites without quartz or biotite, and in composition closely resembles a number of hornblendes from diorites and gabbros.[1]

[1] W. Kunitz, Neues Jahrb. Min., Abt. A. 1930, Beil.-Bd. 60, p. 245. [M.A. 4–200.]

The hornblendes of the appinites and related quartz-orthoclase-plagioclase-hornblende-rock show a wide range of composition and vary with the formation-stage of the rock in which they occur. In the typical coarse appinite two distinct generations of hornblende occur. Brammall[1] has described from Malvern polyvarietal hornblendes from appinitic types which seem to be a feature of rocks of this nature. The earlier is a large brown hornblende set in a finer-grained matrix containing the later well-formed idiomorphic green hornblendes. The presence of two distinct amphiboles in this appinite is sufficient to suggest that one is unstable. The large brown hornblendes are usually completely surrounded by plagioclase and are invariably rimmed by a narrow zone of green hornblende. In many cases this conversion of the brown to the green type has been very much more extensive and the brown hornblendes show large areas of peripheral and sometimes internal replacement. This conversion from the brown to the green hornblende is frequently accompanied by the ejection of small granules of sphene, and the analyses show the brown to be more titaniferous than the green hornblende. Their compositions are seen to be well contrasted, low silica and high alumina in the earlier-formed brown hornblende being replaced by high silica and low alumina in the green. There is also a marked change in the Fe_2O_3/FeO ratio, and the difference in titania has already been noticed.

The hornblendes occurring as medium size phenocrysts in the appinite containing pyroxene (analysis 4) have a similar habit to the large brown hornblende of the coarse appinites. Peripheral conversion to a green hornblende is again common, but in this case there is only a little sphene ejected. Small green hornblendes are also present in the finer matrix and appear to be identical in optical properties and habit with the analysed small green hornblende of the coarse appinite (analysis 3). The instability of these phenocrystal hornblendes is again marked by their readiness to be converted to a green hornblende which is stable in the assemblage in which they occur. The main feature of their composition is their intermediate position between those of the brown and green hornblendes of the coarse appinite in the silica/alumina replacement ratio.

In the hornblende from the quartz-orthoclase-plagioclase-hornblende-rock the stage has been reached in which the hornblende has become almost univarietal in a rock of appinitic type. The grain-size of the rock is also significant. It is one of uniform granular texture in which there is practically no distinction in the size of the hornblendes. Although there

[1] A. Brammall and J. G. C. Leech, read before Min. Soc., March 1936.

are some larger individuals showing pale brown cores with broad rims of green hornblende, no attempt was made to separate the green and the brown varieties and the analysis (no. 5) represents the composite composition of both hornblendes. Some of the smaller hornblendes are also pale brown in colour. In spite of this composite nature, the analysis shows a striking comparision with the small green hornblende of the typical appinite. Silica is high and alumina low, the Fe_2O_3/FeO ratio is closely similar, and the TiO_2, MgO, and CaO show equally close percentages.

The hornblende from the hornblendite is seen to possess the characters of an amphibole of late formation, and shows close affinities with the small later-formed green hornblende of the appinites, and the mineral from the quartz-orthoclase-plagioclase-hornblende-rock. Compared with the average hornblendite[1] the analysis shows high silica and low alumina. The feature of the average hornblendite analysis is one of early hornblende formation, and is closely comparable with both the analyses of the earlier-formed phenocrystal hornblende of the appinites, and the brown hornblende of the injected schists. From these facts it seems probable that the analysis of the hornblende of the hornblendite xenoliths does not represent its original composition, but shows that it has since been converted to a form in equilibrium with the assemblage of the enclosing rock. The magma from which the hornblende[2] crystallizes for the formation of a hornblendite is undoubtedly basic in composition, and hornblendite analyses show that the hornblendes are similar in type to the earlier hornblendes of the Glen Tilt complex. This conversion of the Glen Tilt hornblendite amphibole to a new variety stable in this more acid assemblage is also shown where the hornblende detached from the xenoliths, and incorporated within quartz-diorite, is seen to be in equilibrium with the enclosing rock.

The green hornblende from the hornblende-schist (the one analysed was taken from the central unaffected portion of a large xenolith) presents quite a different composition from the other hornblendes. This is to be expected as it is in no way genetically connected with the rocks of the complex, and arises as a metamorphic product of regional movements prior to the emplacement of the intrusion. It is rich in alumina

[1] R. A. Daly, Igneous rocks and the depth of the earth. New York, 1935. Average hornblendite: SiO_2 42·80, TiO_2 1·62, Al_2O_3 10·55, Fe_2O_3 6·62, FeO 9·16, MnO 0·24, MgO 12·48, CaO 11·67, Na_2O 1·89, K_2O 1·00, H_2O 1·73, P_2O_5 0·24.

[2] The hornblende of some hornblendites is not primary but results from the alteration of pyroxene; e.g. the davainite at Garabal Hill (B. K. N. Wyllie and A. Scott, Geol. Mag., 1913, vol. 50, p. 503).

and correspondingly poorer in magnesia than the igneous hornblende, and shows the highest Na_2O/K_2O ratio. The conversion of this hornblende under two different conditions has been examined. In many localities where the hornblende-schists form the contact-rock, or occur as large xenoliths within the granite, large porphyroblastic hornblendes are seen to grow within the body of the schist and especially in proximity to the narrow permeating veins of volatile-rich emanations from the granite. These porphyroblastic hornblendes lose their green colour, develop a pale brown tint, and are sieved with many inclusions of felspar. As these are expelled the hornblende develops a stronger brown colour and becomes more and more idiomorphic. The chemical changes involved in this conversion from the green hornblende of the schist to the newly-formed brown variety show, from the recalculated analyses compared on the basis of equal volumes, an increase of TiO_2 1·9, MgO 1·5, CaO 1·0, K_2O 0·5, F 0·6 %; and a decrease of Al_2O_3 4·0, Na_2O 0·25, H_2O 0·45 %; while SiO_2, Fe_2O_3, and FeO remained unchanged. These recalculated analyses are given under A, B, C in table II.

TABLE II. Recalculated analyses of hornblendes.

	A.	B.	C.	D.	E.
SiO_2	43·91	44·12	44·07	46·95	44·58
TiO_2	3·71	1·80	3·72	1·73	1·82
Al_2O_3	10·53	14·58	10·57	9·40	14·73
Fe_2O_3	5·00	5·10	5·01	3·65	5·15
FeO	8·84	8·92	8·88	8·34	9·01
MnO	0·17	0·21	0·17	0·11	0·21
MgO	12·24	10·76	12·28	14·38	10·87
CaO	11·73	10·79	11·77	10·48	10·90
Na_2O	1·25	1·50	1·26	1·15	1·52
K_2O	1·09	0·60	1·10	1·29	0·61
$H_2O+105°C.$	0·94	1·41	0·95	1·99	1·42
$H_2O-105°C.$	0·11	0·08	0·11	0·53	0·08
F	0·83	0·22	0·84	—	0·22
	100·35	100·09	100·73	100·00	101·12
Less O for F	0·35	0·09	0·35	—	0·09
	100·00	100·00	100·38	100·00	101·03

A. Analysis 8 recalculated to 100 %.
B. Analysis 7 recalculated to 100 %.
C. Analysis 8 allowance made for the differences in specific gravity.
D. Analysis 9 recalculated to 100 %.
E. Analysis 7 allowance made for the differences in specific gravity.

It is interesting to compare the composition of the brown hornblende developed in the hornblende-schist permeated by granite veins and that

developed from hornblende-schist xenoliths enclosed in the diorite. These schist xenoliths develop a marginal zone rich in large brown hornblende phenocrysts. The formation of this new hornblende results from the instability of the schist amphibole under magmatic conditions, and detached clots of this newly formed hornblende, which do not readily lose their individuality when immersed in the diorite, indicate their comparative stability in the new environment. The diorite penetrates along the laminae of the schist, and the newly formed brown hornblendes tend to be alined along these planes as well as around the xenolithic margins. The conversion of the small, green schist hornblende to the brown takes place very rapidly as the margins or veins are approached, the transition usually being completed within 0·5 cm. The composition of this hornblende shows a greater change than the brown hornblende of the permeated schists, but its most significant feature is that, taken as a whole, it shows a closer resemblance to the hornblende of the diorite than the other hornblendes of the complex. The green hornblende of the schist and the analyses of the newly-developed brown hornblende have been recalculated to 100·00 % and compared on the basis of equal volumes. From the recalculated analyses (B, D, E, table II) the following additions of material are seen: SiO_2 2·35, MgO 3·5, K_2O 0·6, H_2O 0·6 %; and the following losses Al_2O_3 5·3, Fe_2O_3 1·5, FeO 0·75, Na_2O 0·35, and CaO 0·4 %.

If the three analyses are considered together and the brown hornblende developed around the schist xenoliths regarded as the most advanced type, i.e. more stable in a diorite environment, the majority of the oxides show a progressive change. The most important movement of the oxides is a marked decrease in alumina which is counterbalanced by a corresponding increase in the magnesia percentage. Other oxides showing a progressive change are FeO, Fe_2O_3, Na_2O, MnO decreasing, and K_2O increasing. Silica, titania, and lime appear to have no simple relationship. Although there is a gradual increase in the sum of the water and fluorine content, their mutual replacement does not appear to be at all systematic.

III. *The Hornblendes, their Composition and Genetical Relationships.*

The hornblende analyses have been plotted on a trilinear diagram (fig. 1) in order to demonstrate graphically the difference between the earlier and later formed hornblendes and their relations with the hornblendes from the schist and hornblendite. The diagram emphasizes the difference between the large brown 'phenocrystal' hornblendes, whether

occurring in the permeated schist, schist xenoliths, or the typical appinitic development, and the smaller green hornblendes either of the finer matrix of the appinites or that from the quartz-orthoclase-plagioclase hornblende-rock. This rock is considered from the available evidence

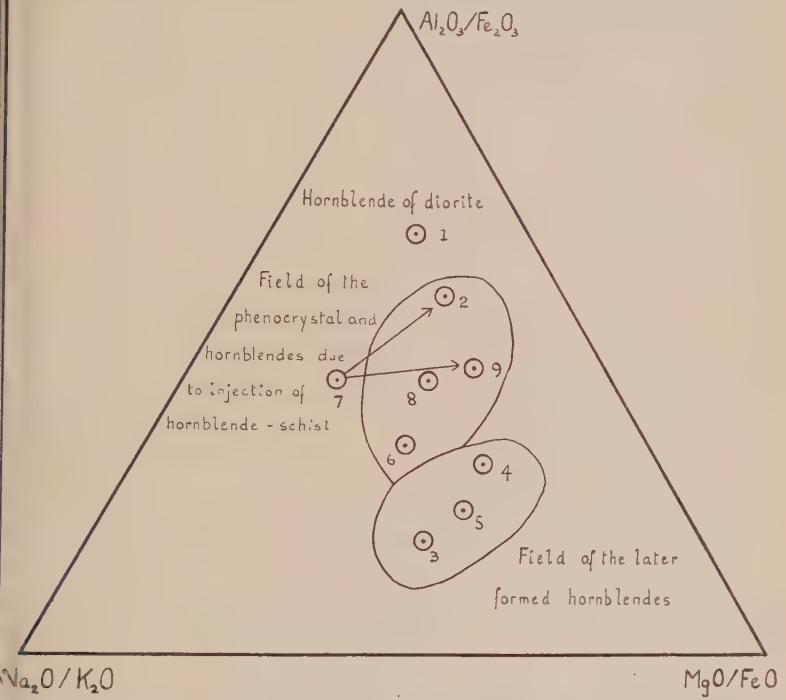


FIG. 1. Trilinear diagram showing the variation in the molecular ratios Al_2O_3/Fe_2O_3–Na_2O/K_2O–MgO/FeO of the earlier- and later-formed hornblendes. The figures refer to the numbers in table I.

to be derived from the hornblendite. From table I the two hornblendes from these two rocks are seen to be closely comparable, and the diagram shows that only a small movement towards the field of the later-formed hornblendes is necessary to convert the hornblendite amphibole to a variety stable in the new environment of the quartz-orthoclase-plagioclase-hornblende-rock. The intermediate chemical position of the hornblende from the medium-grained appinite between the fields of the brown and green hornblende is clearly seen and the aluminous nature of the hornblende from the schist and its brown injection derivatives, altering with a progressive increase in the MgO/FeO ratio, is demonstrated.

Finally, the isolated character of the green hornblende from the ordinary diorite and its lack of genetic relationship with the other hornblendes is fully emphasized. The hornblendes show that the differences in chemical composition between the green and brown varieties, except the earlier-formed greenish-brown hornblende of the diorite, are a consistently higher silica percentage and lower alumina, total alkalis, and titania in

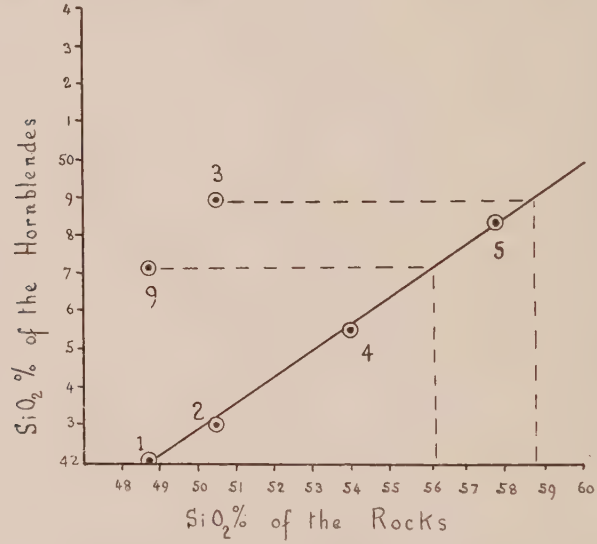


Fig. 2. Diagram showing the relationship between the silica percentage of the hornblendes and of the rocks in which they are contained.

the green, while the total iron is approximately the same in both hornblendes. These results are in agreement with the averages of the main constituents in green and brown hornblendes presented by Graham.[1]

It will be seen from the analyses that the silica percentage of the hornblendes tends to increase as the rock becomes richer in silica. A diagram showing the relationship of the silica percentage of the hornblende and the parent rock is shown in fig. 2. Although there is no rigid relationship between the silica percentage of the hornblende and the rock in which it is formed there is no doubt that an increase in the acidity of the parent rock tends to favour the development of a hornblende richer in silica. Of the plotted analyses which fall off the line showing this relationship only that of the small green hornblende of the typical

[1] W. A. P. Graham, Amer. Min., 1926, vol. 11, p. 121. [M.A. 3-294.]

appinite has been precipitated from even a 'partial' magma, and from a general examination of the rock is inferred to be of later formation, developed at a stage comparable with that of the quartz-orthoclase-oligioclase-hornblende-rock. The brown hornblende of the typical appinite results from the alteration of the original hornblende, whereas the green hornblende is a direct product of the hybridizing 'magma' and the xenolithic rock either hornblendite or hornblende-schist. The small green hornblende is in equilibrium with this later fraction of the rock, that is, with the felspar, but is at a more advanced stage than that represented by the bulk analysis of the rock. This conclusion is strengthened by the diagram, which shows that the hornblende would be more closely related to a rock of approximately 58 % silica. It was suggested in discussing the 'reaction' hornblende of the schist xenolith enclosed in the quartz-mica-diorite, that the more extensive change, compared with the newly-developed hornblende in the injected schist, was due to an attempt to produce a hornblende in equilibrium with the quartz-mica-diorite. From the above diagram it is seen that the silica percentage of the rock should contain between 55 % and 56 % silica, and this is very close to the actual composition of the analysed quartz-mica-diorite.[1] The silica percentage of the brown porphyroblastic hornblende developed in the injected schists indicates possible stability within the silica variation of the appinites. This is not surprising in view of the fact that at least some of the appinite types are derived from the alteration of hornblende-schists. Graham (loc. cit., p. 119), in discussing the chemical composition of hornblendes from eight different rock families, showed that the silica is high and the alumina low in typical hornblendes from granites. This has also been noticed in the late-stage hornblende from the Cairnsmore complex.[2]

A significant feature of the hornblendes of the Glen Tilt rocks is the almost constant percentage of total iron oxides, and except for the hornblende from the diorite (anal. 1) the extreme variation is from 11·87 to 14·29 %. It is well known that the MgO/FeO ratio is higher in the solid phase than in the liquid phase with which it is in equilibrium, and consequently that differentiation will proceed in the direction of a low MgO/FeO ratio. This differentiation trend has not been effective in the development of the Glen Tilt hornblendes, and although analyses 3, 4,

[1] SiO_2 56·73 % for the quartz-mica-diorite of the Glen Tilt complex. A description of the diorites and associated rocks of this complex will be published later.

[2] W. A. Deer, Note on a pegmatitic hornblende from the Cairnsmore complex. Geol. Mag. London, 1937, vol. 74, pp. 359–361. [M.A. 7–25.]

and 6 do show a slightly higher total iron content than the rest there is no decrease in the MgO/FeO ratio. This fall in the ratio MgO/FeO has been observed by Hurlbut[1] in the hornblendes from the Bonsall tonalite, California. Basing his results on the refractive indices of hornblendes in altered gabbro xenoliths, now of dioritic composition, immersed in tonalite, he states that the 'data show a close relation between the various hornblendes, but indicate that the hornblendes of the inclusions are higher in magnesia and lower in iron than those of the tonalite'. The absence of this trend in the hornblendes of Glen Tilt is no doubt to be correlated with their development in rocks not formed under conditions of ordinary crystallization-differentiation. The majority have not formed from a magma of the composition now represented by the rock in which they occur, and it has also been shown that some are not in equilibrium with the assemblage in which they occur.

IV. *Crystal Chemistry of the Hornblendes.*

Although Warren has confirmed the early work of Schaller[2] giving the formula of tremolite as $H_2Ca_2Mg_5(SiO_3)_8$ the statement of Bowen and Posnjak[3] that the amphibole question is probably finally solved seems to be somewhat premature. The hornblende analyses have been calculated according to Warren's[4] formula

$$(OH,F)_2(Na,CaK,)_{2-3}\ (Mg,Fe'',Fe''',Ti,Mn,Al)_5\ [(Si,Al)_8O_{22}]$$

derived from a study of the crystal-structure of tremolite,[5] and extended to include the common hornblendes, that is, on a basis of 24(O,OH,F) atoms to the unit cell. The formulae derived from these calculations are listed below. This type formula had also been developed by Kunitz[6] for certain amphiboles, but this agreement between the earlier chemical study and the later X-ray investigation is not so well maintained by the general amphibole formula proposed by Machatschki,[7] $XY_3(Si,Al)_4(O,OH,F)_{12}$, in which X represents Ca^{++} and Na^{+}, with a little K^{+}, and perhaps Mn^{++}, and Y represents Mg^{++}, Fe^{++}, Al^{+++}, and Mn^{+++}.

[1] C. S. Hurlbut, Amer. Min., 1935, vol. 20, p. 622. [M.A. **6**–223.]

[2] W. T. Schaller, Bull. U.S. Geol. Surv., 1916, no. 610, p. 136. [M.A. **1**–258.]

[3] N. L. Bowen and E. Posnjak, Amer. Journ. Sci., 1931, ser. 5, vol. 22, p. 201. [M.A. **5**–103.]

[4] B. E. Warren, Zeits. Krist., 1930, vol. 72, pp. 493–517. [M.A. **4**–278.]

[5] B. E. Warren, Zeits. Krist., 1929, vol. 72, p. 42. [M.A. **4**–201.]

[6] W. Kunitz, Neues Jahrb. Min., Abt. A, 1930, Beil.-Bd. 60, pp. 200, 206. [M.A. **4**–200.]

[7] F. Machatschki, Zeits. Krist., 1929, vol. 71, p. 222. [M.A. **4**–202.]

TABLE III. Calculation of formulae of hornblendes nos. 1–9.

	Wt. %.	No. of metal atoms on basis of 24(O,OH,F).		Wt. %.	No. of metal atoms on basis of 24(O,OH,F).	
	Hornblende no. 1.			Hornblende no. 2.		
SiO_2	42·11	6·314	8·00	43·01	6·288	8·00
Al_2O_3	10·05	1·776 (1·686 + 0·090)		12·01	2·062 (1·712 + 0·350)	
TiO_2	2·76	0·311	5·21	2·87	0·314	5·21
Fe_2O_3	2·82	0·319		3·35	0·368	
FeO	15·14	1·896		9·07	1·109	
MnO	0·24	0·031		0·19	0·023	
MgO	11·48	2·565		14·00	3·049	
CaO	11·34	1·822	2·39	11·79	1·845	2·34
Na_2O	1·01	0·294		1·08	0·306	
K_2O	1·43	0·274		1·01	0·188	
H_2O+ ...	2·02	2·018	2·02	1·40	1·364	1·75
H_2O- ...	0·06	—		0·06	—	
F	—	—		0·84	0·386	
	100·46			100·68		
Less O for F ...	—			0·36		
	100·46			100·32		

	Hornblende no. 3.			Hornblende no. 4.		
SiO_2	48·92	7·155	8·00	45·50	6·630	8·00
Al_2O_3	5·88	1·010 (0·845 + 0·165)		9·66	1·654 (1·370 + 0·284)	
TiO_2	1·21	0·133	5·11	1·73	0·189	5·17
Fe_2O_3	6·50	0·715		6·06	0·663	
FeO	7·79	0·952		6·90	0·840	
MnO	0·17	0·021		0·18	0·022	
MgO	14·32	3·120		14·61	3·171	
CaO	11·37	1·780	2·25	11·24	1·754	2·26
Na_2O	1·20	0·339		1·20	0·338	
K_2O	0·71	0·132		0·92	0·172	
H_2O+ ...	1·37	1·335	1·46	1·73	1·681	1·68
H_2O- ...	0·18	—		0·19	—	
F	0·27	0·123		trace	—	
	99·89			99·92		
Less O for F ...	0·11			—		
	99·78			99·92		

TABLE III (*continued*).

	Wt. %.	No. of metal atoms on basis of 24(O,OH,F).		Wt. %.	No. of metal atoms on basis of 24(O,OH,F).	
	Hornblende no. 5.			Hornblende no. 6.		
SiO_2	48·32	7·044	8·00	48·96	7·068	8·00
Al_2O_3	6·43	1·101 (0·956 + 0·145)		7·85	1·332 (0·932 + 0·400)	
TiO_2	1·43	0·156	5·10	1·07	0·117	5·29
Fe_2O_3	5·45	0·597		3·62	0·394	
FeO	7·90	0·964		8·25	0·995	
MnO	0·13	0·016		0·12	0·015	
MgO	14·82	3·218		15·69	3·373	
CaO	11·99	1·871	2·28	11·90	1·840	2·23
Na_2O	0·99	0·280		1·04	0·291	
K_2O	0·67	0·124		0·53	0·097	
H_2O+ ...	1·61	1·565	1·57	0·63	0·607	1·25
H_2O- ...	0·06	—		0·08	—	
F	trace	—		1·41	0·642	
	99·80			101·15		
Less O for F ...	—			0·61		
	99·80			100·54		
	Hornblende no. 7.			Hornblende no. 8.		
SiO_2	44·23	6·436	8·00	44·15	6·491	8·00
Al_2O_3	14.62	2·498 (1·564 + 0·934)		10·59	1·829 (1·509 + 0·320)	
TiO_2	1·81	0·198	5·14	3·73	0·411	5·09
Fe_2O_3	5·11	0·559		5·02	0·555	
FeO	8·94	1·087		8·89	1·091	
MnO	0·21	0·026		0·17	0·021	
MgO	10·78	2·337		12·30	2·694	
CaO	10·81	1·685	2·22	11·80	1·858	2·42
Na_2O	1·51	0·424		1·26	0·359	
K_2O	0·61	0·114		1·10	0·207	
H_2O+ ...	1·42	1·377	1·48	0·95	0·930	1·34
H_2O- ...	0·08	—		0·11	—	
F	0·22	0·105		0·84	0·406	
	100·35			100·91		
Less O for F ...	0·09			0·36		
	100·26			100·55		

TABLE III (*continued*).

	Wt. %.	No. of metal atoms on basis of 24(O,OH,F).	
	Hornblende no. 9.		
SiO_2	47·14	6·813	8·00
Al_2O_3 ...	9·44	1·597 (1·187 + 0·410)	
TiO_2	1·74	0·188	5·13
Fe_2O_3 ...	3·66	0·397	
FeO	8·38	1·013	
MnO	0·11	0·013	
MgO	14·44	3·109	
CaO	10·53	1·629	2·19
Na_2O ...	1·15	0·321	
K_2O	1·30	0·240	
H_2O+ ...	2·00	1·927	1·93
H_2O- ...	0·53	—	
F	—	—	
	100·42		

In his work on the crystal-structure and chemical composition of the monoclinic amphiboles Warren (loc. cit., 1930, pp. 508–509) stated that the excess in the value of the (Na,Ca,K) group greater than 2·0, as determined for tremolite, depends on the amount of aluminium replacing silicon in the tetrahedral chains, and that in those hornblendes where approximately one quarter of the silicon is replaced by aluminium the value of the (X) group (Na,Ca,K) becomes nearly 3·0. Although this is the case with some hornblendes (e.g. those chosen by Warren and included in his table, p. 506) it is far from being a general rule as seen by a number of recent hornblende analyses.[1] This is clearly the case of the Glen Tilt minerals, for although they show a very slight general tendency to increase the value of the (X) group from 2·0 towards 3·0 with increasing replacement of silicon by aluminium there is no close relationship between these two factors. In the general case the value of the (X) group does not appear to be dependent so much on the silicon/aluminium replacement as on the percentage of alkalis in the hornblende composition. The amount of lime in the constitution, not only of common hornblende but also of tremolite and actinolite, tends to be almost constant, so that any increase in the percentage of total alkalis is effective in increasing the value of the (X) group, and this is the case of those

[1] J. D. W. Wiseman. Quart. Journ. Geol. Soc. London., 1934, vol. 90, pp. 368–369, 382–384 [M.A. 6-224]; S. R. Nockolds, Geol. Mag. London, 1935, vol. 72, p. 310; and others.

analyses chosen by Warren. The Glen Tilt hornblendes show a relatively constant and moderately low amount of total alkalis, but a considerable range of alumina, with a consequently small variation in the value of the (X) group for very larger difference of silicon/aluminium replacements.

The distinction between the earlier- and later-formed hornblendes of the complex is seen in the varying values of the replacements listed below:

Hornblendes.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
A.	1·69	1·71	0·85	1·37	0·96	0·93	1·56	1·51	1·19
B.	0·09	0·35	0·16	0·28	0·14	0·40	0·93	0·32	0·41
C.	0·39	0·34	0·25	0·26	0·28	0·23	0·22	0·42	0·19

A. Aluminium replacing silicon.
B. Aluminium replacing magnesium.
C. Excess of (X) group over 2.

The table indicates the very rough correlation between the increasing value of the (X) group with the increasing replacement of silicon by aluminium. The isolated position of the hornblende from the normal diorite is seen in the very high replacement of silicon by aluminium, and the low replacement of magnesium. It emphasizes the sympathetic decrease in the MgO and FeO in the conversion of the green hornblende from the schist to the brown hornblendes of the injected schists, and the convergence of these towards the structure and composition of the later-formed hornblendes. This is especially marked in the 'reaction' hornblende developed at the margin of the schist xenolith in the quartz-mica-diorite (no. 9).

There are only two relationships which the hornblende composition must satisfy: the first is the hornblende crystal-structure; the second, that the total positive and negative valencies must balance. The occupation of the vacant AA' positions of Warren (loc. cit., 1930, p. 512) in the tremolite structure by alkalis is of course insufficient in itself to balance the negative valency excess caused by the replacement of silicon by aluminium. This was demonstrated graphically by plotting the amount of aluminium replacing silicon against the excess of the value of the (X) group over 2·0 from a large number of analyses from Doelter,[1] Kunitz (loc. cit., pp. 244–245), and others, and in only two cases was the balance obtained, solely by the increase of the (X) group. A selection of the formulae obtained from these analyses showing the replacement values

[1] C. Doelter, Handbuch der Mineralchemie, 1914, vol. 2, pt. 1, pp. 610–620.

s given below. The deficiency of positive ions is, however, further compensated by the replacement of divalent magnesium by sesquioxides and tetravalent titanium. This is usually slightly offset by the replacement of divalent calcium by univalent alkalis when the value for Ca^{++} is less than 2·0.

I. $(OH)_{1\cdot8}$ (Ca, &c.)$_2$ $Na_{0\cdot3}$ Mg, &c.$_{4\cdot5}$ (Fe‴,Ti,Al)$_{0\cdot7}$ $[(Si_{7\cdot1}Al_{0\cdot9})\ O_{22}]$.
II. $(OH)_{1\cdot6}$ (Ca, &c.)$_2$ $Na_{0\cdot7}$ Mg, &c.$_{4\cdot4}$ (Fe‴,Ti,Al)$_{0\cdot8}$ $[(Si_{6\cdot3}Al_{1\cdot7})\ O_{22}]$.
III. $(OH)_{1\cdot4}$ (Ca, &c.)$_2$ $Na_{0\cdot7}$ Mg, &c.$_{4\cdot1}$ (Fe‴,Ti,Al)$_{1\cdot1}$ $[(Si_{6\cdot3}Al_{1\cdot7})\ O_{22}]$.
IV. $(OH)_2$ (Ca, &c.)$_2$ $Na_{0\cdot5}$ Mg, &c.$_{4\cdot5}$ (Fe‴,Ti,Al)$_{0\cdot7}$ $[(Si_{6\cdot4}Al_{1\cdot6})\ O_{22}]$.
V. $(OH)_2$ (Ca, &c.)$_2$ $Na_{0\cdot4}$ Mg, &c.$_{4\cdot3}$ (Fe‴,Ti,Al)$_{0\cdot9}$ $[(Si_{6\cdot4}Al_{1\cdot6})\ O_{22}]$.
VI. $(OH)_2$ (Ca, &c.)$_2$ $Na_{0\cdot7}$ Mg, &c.$_{4\cdot2}$ (Fe‴,Ti,Al)$_{1\cdot0}$ $[(Si_{6\cdot4}Al_{1\cdot6})\ O_{22}]$.
VII. $(OH)_{2\cdot1}$ (Ca, &c.)$_2$ $Na_{0\cdot3}$ Mg, &c.$_{3\cdot2}$ (Fe‴,Ti,Al)$_{1\cdot7}$ $[(Si_{6\cdot3}Al_{1\cdot7})\ O_{22}]$.
VIII. $(OH)_{1\cdot9}$ (Ca, &c.)$_2$ $Na_{0\cdot5}$ Mg, &c.$_{4\cdot1}$ (Fe‴,Ti,Al)$_{0\cdot9}$ $[(Si_{6\cdot7}Al_{1\cdot3})\ O_{22}]$.
IX. $(OH)_{1\cdot5}$ (Ca, &c.)$_2$ $Na_{0\cdot5}$ Mg, &c.$_{3\cdot9}$ (Fe‴,Ti,Al)$_{1\cdot3}$ $[(Si_{6\cdot4}Al_{1\cdot6})\ O_{22}]$.
X. $(OH)_{1\cdot8}$ (Ca, &c.)$_2$ $Na_{0\cdot2}$ Mg, &c.$_{4\cdot2}$ (Fe‴,Ti,Al)$_{0\cdot9}$ $[(Si_{7\cdot0}Al)\ O_{22}]$.

Nos. I–VI are from Kunitz's hornblende analyses (loc. cit., p. 245) nos. 4–9 respectively.

No. VII. Doelter, p. 620. Hornblende from diorite. Schwarzenberg, Vosges.

No. VIII. Doelter, p. 619. Hornblende from hornblende-gabbro. Beaver Creek, California.

No. IX. Doelter, p. 619. Hornblende from anorthite-diorite-schist. Kremstal, Austria.

No. X. Doelter, p. 614. Hornblende from quartz-diorite. Mount Hoffman, California.

The value of the (Y) group in the common hornblende is consistently higher than the value 5 for the tremolite structure, and it seems likely that some of the vacant *AA′* positions may be occupied by ions of the (Y) group. This high value of the (Y) group is significant and also appears to be related to the value of the hydroxyl-fluorine group. Warren (loc. cit., 1930, p. 516) has commented on the possibility that in cases in which there has been a large replacement of magnesium by sesquioxides and titanium the (OH,F) group may be partly replaced by oxygen. In such cases the value of the (Y) group is usually considerably greater than 5·0 and the value of (OH,F) well below 2·0.[1] The replacement of OH^- and F^- by O^{--} then becomes necessary to maintain the

[1] E. S. Larsen, J. Irving, F. A. Gonyer, and E. S. Larsen (3rd), Amer. Min., 1937, vol. 22, p. 898. [M.A. 7–31.] Three analyses of hornblendes from the Tertiary volcanic rocks of the San Juan region, Colorado, support this suggestion. The authors state that if Fe″ is replaced by Fe‴ some replacement, such as OH by O, must take place, a fact which is confirmed by the analyses, the formulae of which are given below:

1. $(OH,F)_{0\cdot6}$ $(Ca,Na)_{2\cdot4}$ $(Mg,Fe'',Fe''',Mn,Ti,Al)_{5\cdot25}$ $[(Si,Al)_8\ O_{22}]$.
2. $(OH,F)_{1\cdot2}$ $(Ca,Na)_{2\cdot4}$ $(Mg,Fe'',Fe''',Mn,Ti,Al)_{5\cdot25}$ $[(Si,Al)_8\ O_{22}]$.
3. $(OH)_{0\cdot8}$ $(Ca,Na)_{2\cdot5}$ $(Mg,Fe'',Fe''',Mn,Ti,Al)_{5\cdot4}$ $[(Si,Al)_8\ O_{22}]$.

chemical valency which is upset by the introduction of additional ions in the (Y) group. This becomes more obvious in the case of the basaltic hornblendes and the anhydrous amphiboles which show characteristically a very low value for the (OH,F) group, and a consistently large replacement of magnesium by titanium and ferric iron. This oxygen/hydroxyl replacement is accepted by Berman and Larsen,[1] who write the hornblende formula, showing the limits of replacement as:

$$(O,OH,F)_2(Ca,Na_2)Na_{0-1},\ Mg,(Mg,Al,\&c.)_4(Al,Si)_2(Si_6O_{22}),$$

but the restriction of the minimum value for silicon to 6·0 does not appear to hold in the case of some basaltic hornblendes.[2]

V. The Relationship of the Optical Properties and Chemical Composition.

The study of the Glen Tilt amphiboles shows that the hornblendes remain the most difficult series of the common rock-forming minerals to estimate chemically from their optical properties. Nevertheless, some indication of their constitution can be obtained from the optical properties and especially from the refractive indices. The most important factor effecting the refractive indices is the magnesia/ferrous iron ratio. Billings[3] has shown that the optical properties of fermaghastingsite and magnesiohastingsite are largely determined by this ratio. With increasing ferrous iron the refractive indices as well as the specific gravity increase, and these changes are accompanied by a decrease in the optic axial angle. These optical effects are also described by Marchet[4] in the hornblendes from the Waldviertel, Austria. Ford's[5] investigations and Wiseman's study (loc. cit., p. 384) of hornblendes under conditions of progressive metamorphism conform to this general rule. Barnes[6] also observed that the conversion of green hornblende to brown hornblende on heating was accompanied by a decrease in the extinction-angle ($\gamma : c$). This is seen in the relationship of the green and brown hornblendes of the Glen Tilt complex.

[1] H. Berman and E. S. Larsen, Amer. Min., 1931, vol. 16, p. 142. [M.A. **5**–216.]

[2] Y. Kawano, Proc. Imp. Acad. Tokyo, 1934, vol. 10. pp. 349–352. [M.A. **6**–190.] Analysis of basaltic hornblende:

SiO_2 38·30, TiO_2 6·06, Al_2O_3 12·87, Fe_2O_3 7·98, FeO 6·96, MnO 0·12, MgO 11·79, CaO 10·47, Na_2O 3·11, K_2O 1·30, H_2O+ 1·10, F 0·05, giving the formula: $(OH,F)_{1\cdot1}\ (Ca,Na,K)_{2\cdot8}\ (Mg,Fe'',Fe''',Mn,Ti)_{5\cdot1}\ [(Si_{5\cdot7}\ Al_{2\cdot3})O_{22}]$.

[3] M. Billings, Amer. Min., 1928, vol. 13, p. 292. [M.A. **4**–39.]

[4] A. Marchet, Min. Petr. Mitt. (Tschermak), 1925, vol. 38, p. 494. [M.A. **3**–82.]

[5] W. E. Ford, Amer. Journ. Sci., 1914, ser. 4, vol. 37, p. 179.

[6] V. E. Barnes, Amer. Min., 1930, vol. 15, p. 393. [M.A. **4**–391.]

The ratio of ferric to ferrous iron does not appear to be as important as the MgO/FeO ratio in the common hornblendes (compare Ford's diagram, p. 192). This ratio, however, becomes increasingly important in the case of the basaltic and oxyhornblendes. The ferric/ferrous iron ratios of the Glen Tilt hornblendes have been plotted on Barnes' diagram (loc. cit., p. 413) showing the relationship between ferrous and ferric iron in analysed samples of common, basaltic, and heated hornblendes. They all fall in the common hornblende field, although in numbers 3 and 4 the ferrous/ferric ratio approaches unity. The ratio Fe″/Fe‴ does not appear to become important in effecting the optical properties until the Fe‴/Fe″ ratio is at least 2/1. The most difficult oxides to estimate from the optical properties are silica and alumina. This is illustrated by analyses 2, 5, 6, in which the values for α and γ are very similar but in which the silica and alumina percentages vary considerably. On the whole, increasing refractive index in hornblendes of diorites indicates an increase in alumina and a decrease in silica (see Ford's diagrams 1 and 2, p. 183). The increase of refractive index in the hornblendes of granites is usually due to a large increase in iron and not the increase in the silica/alumina ratio that accompanies it. Lime is very constant in value in all the common hornblendes and has no obvious influence on the refractive index.

VI. The Colour of the Hornblendes.

The question of the colour of the hornblendes still remains an unsolved problem. Although it is quite evident that the ratio Fe_2O_3/FeO becomes important in the heated oxyhornblendes,[1] the change from green to brown hornblende is quite independent of this ratio in naturally occurring minerals. The Fe_2O_3/FeO ratio is increased in the green hornblendes of Glen Tilt, and in two recent analyses of green hornblende from the Burcell sills, British Columbia,[2] the ratio approaches 2:1. Graham (loc. cit., p. 121) has also stressed the relative unimportance of the state of the iron oxidation and its influence on the optical properties of hornblende. In a general study of green minerals MacCarthy[3] has shown that though the majority of green minerals are distinctly ferrous, that this is by no means always true, and a fair number of ferric minerals are evident.

[1] V. E. Barnes, loc. cit., p. 413; W. A. P. Graham, loc. cit., p. 122; A. Belovsky, Neues Jahrb. Min., 1891, p. 291.

[2] H. M. A. Rice, Amer. Min., 1935, vol. 20, p. 308. [M.A. 6–119.]

[3] G. R. MacCarthy, Amer. Min., 1926, vol. 11, p. 321. [M.A. 4–251.]

The most noticeable increase in the conversion of the green hornblende of the schist to a deep brown hornblende in the permeated portions of the schist is the increase in titania. Winchell[1] and Graham (loc. cit., p. 121) have already suggested that the differences of green and brown hornblendes lies in the amount of titanium occurring as TiO_2 and Ti_2O_3. The correlation between a brown colour and a high titanium content is supported by the general characteristics of basaltic hornblendes. The specific increase or decrease of titanium is not, however, the only deciding factor. This is seen in the brown 'reaction' hornblende, of the hornblende-schist xenoliths immersed in the quartz-mica-diorite in which the change from green to brown hornblende is unaccompanied by any increase in the percentage of titania. In the greenish-brown hornblendes of the appinites the large range of tint developed with a corresponding difference in chemical composition, the increase in the brown component does appear to be accompanied by an increase in the titanium percentage. This increase in the greenish-brown hornblendes has been noticed by Nockolds,[2] but in those hornblendes of the Glen Tilt complex with a well-developed deep green colour this correlation does not hold. This suggests that the colour problem of the hornblendes does not rest simply on the percentage of any one constituent, but rather on the type of ions in the hornblende structure, and is probably dependant on the state of the titanium oxidation as Ti‴ or Ti⁗.

This study was carried out in the Department of Mineralogy and Petrology, Cambridge, and the writer wishes to thank Professor C. E. Tilley for his encouragement and interest during the progress of the work.

[1] A. N. Winchell, Amer. Journ. Sci., 1924, ser. 5, vol. 7, p. 303. [M.A. 2–304.]

[2] S. R. Nockolds, personal communication.

The Kaalijärv meteorite from the Estonian craters.

(With Plate III.)

By L. J. Spencer, C.B.E., M.A., Sc.D., F.R.S.
Formerly Keeper of Minerals in the British Museum.

[Read January 27, 1938.]

KAALIJÄRV is a crater-lake on the estate Kaali (järv = lake in the Estonian language) at 58°24′N., 22°40′E. Known in German as Sall, this locality is 20km. NE. of Arensburg (= Kuresaare) on the Baltic island of Oesel (= Saaremaa). On the level agricultural country a thickly wooded knoll 6–7 metres high is seen. Inside there is a crater 35½ m. in depth, the circular rim of which measures 92–110 m. across. The lake at the bottom is about 60 m. across. The rock of the district is horizontally bedded Silurian dolomite with a covering of glacial deposits. The rim of the crater consists of fragmentary materials, and the steeper inner slopes show the beds of dolomite dipping outwards as a dome at angles of 30–40°. Near by, on an area of ¾ sq. km., are five other smaller craters similar in character, and at least three other depressions that have been filled with stones collected from the tilled fields.

These craters present many points of resemblance to the famous Meteor Crater in Arizona and the Henbury craters in Central Australia, but they were known much earlier. They have often been described, first by J. von Luce in 1827, and many suggestions have been made as to their mode of origin. They have been thought to be earthworks made by man, and they have been compared with the volcanic crater-lakes of the Eifel and the Campi Flegrei. Other modes of origin that have been suggested are: (1) gas explosions, (2) oozing out of a bed of clay, (3) karst weathering of the dolomite, (4) solution of rock-salt from salt domes, (5) expansion of anhydrite by hydration. Eruptions of natural gas are known in Estonia from bituminous beds of the *Dictyograptus* (*Dictyonema*) shales of Cambrian age and the Kuckers beds of Ordovician age; and as these beds underlie the Silurian dolomite of the island of Oesel, the formation of the craters by gas explosions seemed not improbable.[1] I was myself inclined to this view until the recent finding

[1] O. von Linstow, Der Krater von Sall auf Oesel. Centr. Min., 1919, pp. 326–339.

of meteoritic material. At a later date (J. Kalkun,[1] 1922) the crater were compared with the Meteor Crater in Arizona.

A detailed survey of the craters with excavations and borings wa undertaken in 1927 by Mr. Ivan Reinvald, Inspector of Mines in Estonia He found tilted, shattered, powdered, and 'burnt' dolomite, and in his paper[2] he makes out a strong case for the meteoritic origin of the craters, although no trace of meteoritic material could be found. He concluded that they are explosion craters, attributing the explosion to the generation of steam from ground-water when the meteorites struck the earth. He returned to the work again in 1929,[3] but still no meteoritic material was found. Under his guidance the locality was visited by A. Wegener[4] in 1927, A. R. Hinks[5] in 1933, and Dr. Clyde Fisher[6] in 1936, each of whom was convinced of the meteoritic origin of the craters. A later discussion by W. Kranz,[7] based on Reinvald's papers, supports the same view. A review was given by me in 1933.[8] The lack of meteoritic iron at this locality is explained by Mr. Reinvald by the fact that the land here has been tilled from time immemorial, and any masses of metal would have been already gathered for use as implements.[9]

With remarkable persistence Mr. Reinvald again returned to the work of excavation in July, 1937, when he was at last rewarded by finding

[1] J. Kalkun [= J. Kaljuvee], [Üdine geoloogia. Tallinn, 1922, p. 101] quoted by I. Reinwaldt, loc. cit., 1928; J. Kaljuvee, Die Grossprobleme der Geologie. Tallinn, 1933, pp. 102–108. [M.A. 5–410.]

[2] I. Reinwaldt, Bericht über geologische Untersuchungen am Kaalijärv (Krater von Sall) auf Ösel. Mit Beiträgen von A. Luha. Sitzungsber. Naturfors. Gesell. Univ. Tartu, 1928, vol. 35, pp. 30–70, 8 pls.; separate as Publ. Geol. Inst. Univ. Tartu, 1928, no. 11, 42 pp., 8 pls. [M.A. 5–17.]

[3] J. A. Reinvaldt, Kaali järv—the meteorite craters on the island of Ösel (Estonia). Ibid., 1933, vol. 39 (for 1932), pp. 1–20, 3 pls.; separate, ibid., 1933, no. 30, 20 pp., 3 pls. [M.A. 5–301.]

[4] E. Kraus, R. Meyer, and A. Wegener, Untersuchungen über den Krater von Sall auf Ösel. Gerlands Beitr. Geophysik, 1928, vol. 20, pp. 312–378, 1 pl., 10 text-figs., pp. 428–429. [M.A. 5–17.]

[5] A. R. Hinks, Geogr. Journ. London, 1933, vol. 82, p. 375.

[6] C. Fisher, The meteor craters in Estonia. Nat. Hist., Amer. Mus. Nat. Hist., 1936, vol. 38, pp. 292–299, 10 figs. [M.A. 7–73.]

[7] W. Kranz, "Krater von Sall" auf Ösel, wahrscheinlich "Meteorkrater". Gerlands Beitr. Geophysik, 1937, vol. 51, pp. 50–55. [M.A. 7–73.]

[8] L. J. Spencer, Meteorite craters as topographical features on the earth's surface. Geogr. Journ. London, 1933, vol. 81, p. 233; reprinted in Ann. Rep. Smithsonian Inst. Washington for 1933, 1935, p. 315. [M.A. 5–301, 6–208.]

[9] A similar explanation is given for the absence of meteoritic iron in India (as contrasted with America and Australia). Of the 111 recorded Indian meteorites only one is a found iron.

small rusted fragments of meteoritic iron, and so definitely proving that he had correctly interpreted his previous work.[1] During fourteen days with six workmen and carefully sorting the loose material dug out from the inside of the craters, thirty fragments were found. Two of these were found in crater no. 5, which has a diameter of 10–13 m., and the remainder in the smaller part of the oval (double) crater no. 2, which measures 53×36 m. The fragments range from 24 to 0·1 grams, and the total weight amounted to only about 100 grams.

A selection of this precious material has been very kindly submitted to me by Mr. Reinvald for description, and he has very generously presented three pieces for the British Museum collection of meteorites.[2] The ten fragments sent for examination range in weight from 18·6 to 0·3 grams. They have the appearance of bits of iron-shale, but the heaviness of some pieces suggests that some metal is present inside. This iron-shale or rust is flaky and rather friable on the surface, but inside it is hard and takes a good polish. The surface is often in part incrusted with pale yellowish calcite which is minutely botryoidal, and clearly a secondary deposit formed during the period that the fragments were buried in the ground in association with the dolomite-rock.[3]

Three of the heavier and more suitably shaped pieces were ground down until a surface of metal appeared, which was then polished and etched for study. Curiously, each of them showed a different type of structure, due perhaps to the small size of the areas. All of them came from crater no. 2.

Section no. 1 (pl. III).—This is the largest piece and had already been ground down and very well etched by Mr. Reinvald; it then weighed 18·6 grams. Fig. 1 reproduces a photograph (4 diameters natural size) of the etched surface as received; and fig. 2 the same surface after it had been repolished and re-etched with dilute nitric acid (and photographed in a different inclination of the light). The fragment measures $3\times2\frac{1}{2}$ cm., and the irregular area of metal on the polished surface about $2\frac{1}{2}\times1\frac{1}{4}$ cm.

[1] Brief mention of this discovery has been made by I. A. Reinwald, Der Krater von Sall (Kaali järv)—ein Meteorkrater-Feld in Estland. Natur und Volk, Ber. Senckenb. Naturfor. Gesell., Frankfurt am Main, 1938, vol. 68, pp. 16–24, 7 figs. [M.A. 7–73.]

[2] Rock specimens from the craters were presented to the British Museum by Mr. Reinvald in 1932.

[3] A similar secondary deposit of calcium carbonate is seen on the iron-shale of the Hoba (South-West Africa) meteorite which had lain in surface limestone (L. J. Spencer, Min. Mag., 1932, vol. 23, p. 7). It is clearly not the result of the welding of cosmic and telluric material at the time the meteorite fell, as suggested by P. Range and R. Schreiter (1931). [M.A. 5–11.]

with a surrounding area of iron-shale. Conspicuous are irregular areas or blebs of bright tin-white schreibersite (dark in fig. 1, and light in fig. 2). This abundance of schreibersite recalls the La Primitiva (Angela) meteoritic iron from Chile.[1] Prominent also are three areas traversed by a fine system of parallel bars, which in a certain inclination with respect to the light shine up with a bright tin-white colour. These are at first suggestive of bars of taenite in plessite areas. Other irregular bars and lines and numerous bright specks (fig. 2) are scattered through the groundmass. These bright bars, lines, and specks all appear to be schreibersite. They have the same colour and lustre as the larger blebs of schreibersite, and they are anisotropic in reflected polarized light. Further, they are not attacked by copper ammonium chloride solution. Partly enveloping and penetrating blebs of schreibersite are small patches and strings of graphite. No troilite was detected. The groundmass is very fine grained under the highest power of the microscope, suggesting an ataxite, but there is no oriented sheen in reflected light.

Section no. 2.—This fragment weighed 5·6 grams as received. After grinding down and polishing it weighed 4·9 grams. The metal area on the polished surface measures $1\frac{1}{2} \times \frac{1}{2}$ cm. It shows curved lines of taenite 1–2 mm. apart with dull granulated kamacite between, and the structure much resembles that of the distorted fragments from the Henbury meteorite craters in Central Australia.[2] In copper ammonium chloride solution copper is deposited over the whole surface, but this is readily wiped off except on the thin lines of taenite. The taenite is then shown prominently by the copper colour, and a small plessite area with bars of taenite also becomes evident.

Section no. 3.—This fragment weighed 2·7 grams and after grinding and polishing 2·0 grams. The polished metal area, $1 \times \frac{1}{2}$ cm., shows no obvious structure and no oriented sheen in reflected light. It may be described as an ataxite. No schreibersite was seen. Material for analysis was taken from this specimen.

Of these three sections, nos. 1 and 3 suggest an ataxite, the former rich in schreibersite; while no. 2 suggests a medium octahedrite, but much distorted, and showing the effects of heating, which probably happened at the time the meteorite fell and exploded.

A preliminary chemical analysis was made by Mr. A. Väärismaa of the Tallinn Technical University, using a fragment weighing 0·4 gram from crater no. 2. His results are Fe 84·04, Ni 6·45, insoluble 0·53 = 91·02.

[1] G. T. Prior, Min. Mag., 1914, vol. 17, p. 131, pl. VI, figs. 2 and 3.

[2] L. J. Spencer, Min. Mag., 1933, vol. 23, p. 230, pl. XIV, fig. 8.

This gives a ratio Fe : Ni = 13; but it is evident from the deficiency in the total that the material analysed included iron rust, and this is no doubt less rich in nickel than the metal from which it was derived.

A micro-chemical analysis was made by Dr. M. H. Hey in the Mineral Department of the British Museum on 6·6 mg. of metal removed with a dental drill from the surface of section no. 3. His results are Fe 91·50, Ni 8·32 = 99·82. The 'Fe' includes any cobalt and copper, but these can be present in only small amount. Phosphorus was tested for but not found. Sulphur was not determined. The ratio Fe : Ni is here 11. The following is Dr. Hey's note on the method of analysis:

> The metal was dissolved in dilute hydrochloric acid, evaporated, and oxidized with nitric acid, and the solution filtered. There was no insoluble residue. After addition of tartaric acid, the solution was made ammoniacal and the nickel precipitated with dimethylglyoxime, filtered off, dissolved and reprecipitated, dried, and weighed as $Ni(C_4H_7O_2H_2)_2$. In the evaporated filtrates, acidified with acetic acid, iron, cobalt, and copper were precipitated with 8-hydroxyquinoline, and the combined precipitate filtered off, dried, and weighed; neglecting its cobalt and copper content, the precipitate was taken to be $Fe(C_9H_6ON)_3$ and its iron content calculated.

Three meteorites have been previously recorded from Estonia (= Eesti):

Oesel. A shower of stones fell on May 11, 1855, on the Kaanda estate and some in the sea in the Taga laht (laht = gulf), on the NW. coast of the island of Oesel (= Saaremaa), 58° 30′ N., 22° 2′ E. Only fragments weighing 6 kg. were recovered.

Pillisfer. A shower of stones fell on August 8, 1863, at several places near Pillisfer (= Pilisvere), 58° 40′ N., 25° 44′ E. Stones weighing about 4, 7½, 1½, and ¼ kg. were recovered.

Tennasilm. A stone weighing 28½ kg. fell on June 28, 1872, on the Sikkensaare farm near the village of Tennasilm (= Tänasilma), 58° 44′ N., 24° 54′ E.

Postscript.

In December, 1937, Mr. I. Reinvald received a mass of iron weighing 2·4 kg. that had been found at a distance of ¾ km. from the main crater of Kaalijärv. It had been dug up from a depth of 50–60 cm. in the neighbouring estate of Köljala by students of the agricultural school when repairing foundations in the courtyard. Naturally Mr. Reinvald had hopes that this was meteoritic iron and that it might have some connexion with the meteorite craters, but a preliminary analysis showed the absence of nickel (Fe 91·90, P 0·85 %), and he was puzzled

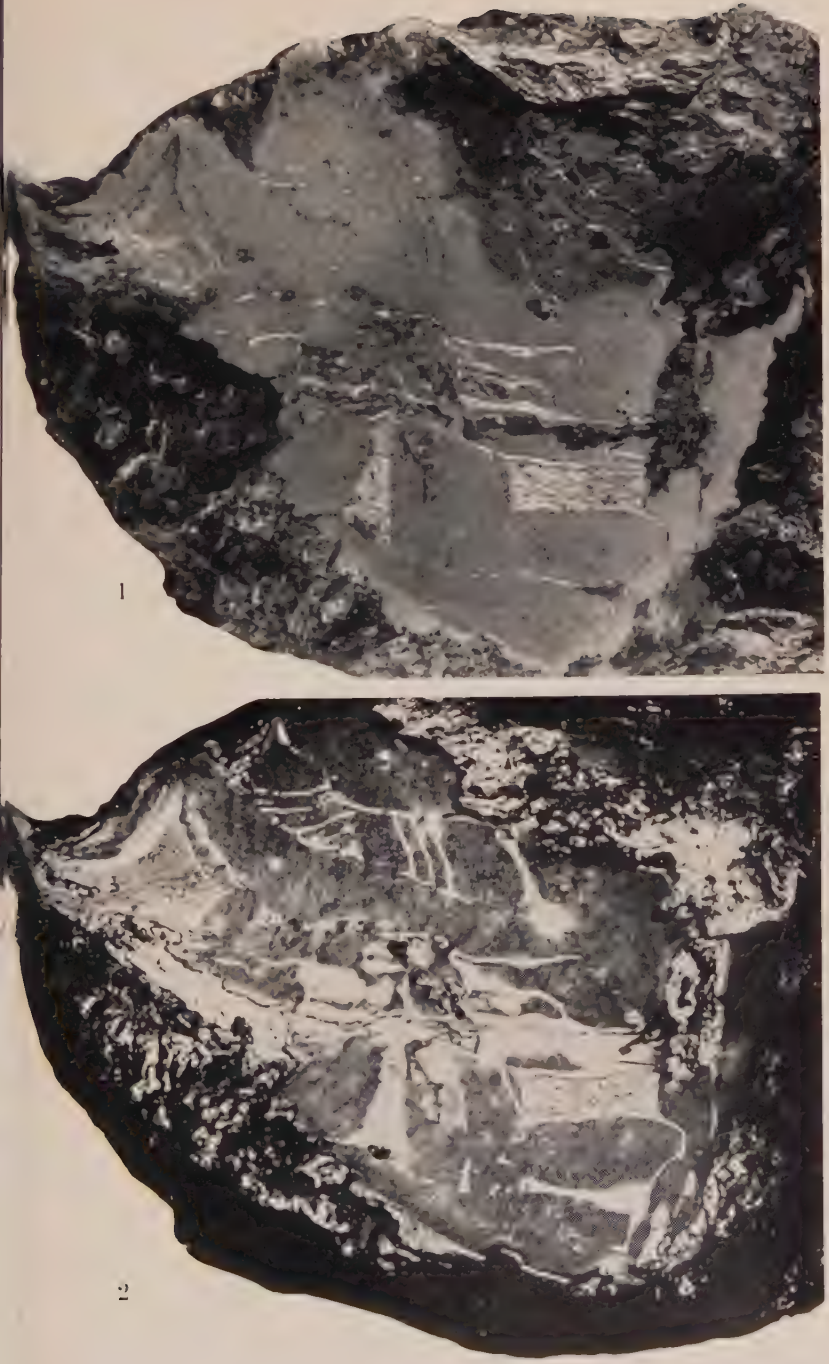
by the curious structure shown on a polished surface. He therefore very kindly sent the whole specimen for further examination.

The mass has an irregular rounded shape, about 11 cm. across, but with none of the concavities and pittings often to be seen on meteoritic irons. There is a thick crust of dark brown iron oxide, which is very hard and compact, and in part shows a minutely mamillated surface. It is strongly magnetic, and has an indistinct laminated structure, being very like the iron-shale found around weathered meteoritic iron. The polished (unetched) surface of the metal shows from numerous centres stellate groups (about 1 mm. across) of curved threads, the whole surface being covered with an intricate network of minute curved lines. These are cross-sections of flakes of graphite, which on a highly polished surface are worn down below the general level. Minute bright flakes of graphite are seen on fractured surfaces of the iron and also in the iron-shale. A fragment of the iron dissolved in hydrochloric acid left a residue of about 5 % consisting mainly of flakes of graphite. No nickel was detected. This pseudo-meteorite is therefore a block of grey cast iron.

Explanation of Plate III.

The Kaalijärv meteorite from crater no. 2, Oesel, Estonia.

Photographs by D. L. Williams, Mineral Dept., British Museum, with different inclination of the light in the two figures. ×4. The light areas in fig. 2 are schreibersite in a grey ataxite groundmass, and the surrounding dark portion is iron-shale.



L. J. SPENCER : KAALIJÄRV METEORITE

A re-examination of cliftonite.

By Max H. Hey, M.A., D.Sc.
Assistant-Keeper in the Mineral Department of the British Museum.

[Read November 4, 1937.]

CLIFTONITE was described by Sir Lazarus Fletcher[1] in 1887 as 'a cubic form of graphitic carbon'. He put forward reasons for regarding it as a new allotropic modification of carbon and other reasons suggesting that it is a pseudomorph of graphite after some cubic mineral, perhaps diamond, but did not definitely favour either view. On the evidence available hitherto, both suggestions were clearly possible.

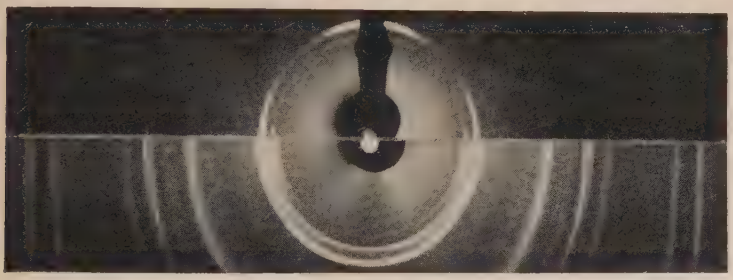


Fig. 1. X-ray photographs of cliftonite (upper) and graphite (lower).

At the suggestion of Dr. H. Berman, we have examined the original material by X-ray methods, comparing it with a specimen of graphite (B.M. 86685) from Grenville, Quebec. Although very thoroughly powdered, the graphite shows very marked orientation in the powder photograph (fig. 1, bottom half), the flaky crystals nearly all lying parallel to the supporting glass fibre, as is shown by the concentration of the (0001) reflection into short arcs.

The specimen of cliftonite examined was a small cube, Sir Lazarus Fletcher's no. 1, and was rotated about an [001] axis. The resulting photograph (fig. 1, top half) shows quite clearly that cliftonite is an oriented pseudomorph of graphite, the graphite crystals, the dimensions of which are not less than $0{\cdot}1\mu$, being arranged with their c-axes parallel to the three [001] axes of the cube. The nature of the original mineral remains uncertain, as no diffractions other than those of graphite were observed.

[1] L. Fletcher, Min. Mag., 1887, vol. 7, p. 121; 1899, vol. 12, p. 171.

Australites: a unique shower of glass meteorites.[1]

By Charles Fenner, D.Sc.
University of Adelaide.

[Read March 10, 1938.]

IT is just over a hundred years since Charles Darwin, during his great voyage, visited Sydney, New South Wales. While there, he was given, by the explorer Major Sir Thomas Mitchell, a small and curiously shaped glassy object. In his 'Geological Observations' (1844) Darwin figured this object and speculated as to its origin, which he suggested was volcanic. This is the first recorded reference to what are now known as australites, many tens of thousands of which have been collected from widespread localities over the whole of southern Australia.

About fifty years before the first appearance of Darwin's australite, references occurred in literature to numberless fragments of greenish glass found in Bohemia and Moravia; these fragments came to be called moldavites. Later, in 1900, Professor F. E. Suess, of Vienna, linked up the moldavites and the Australian objects and gave them the general name of tektites ('melted'). Since then several other groups of tektites have been discovered and these may be briefly listed as follows:

(*a*) Moldavites, in Bohemia and Moravia.
(*b*) Australites ('blackfellows' buttons'), in southern Australia.
(*c*) Darwin Glass (queenstownites), in north-western Tasmania.
(*d*) Billitonites, in Billiton and other East Indian islands.
(*e*) Rizalites, in the Philippine Islands.
(*f*) Javanese tektites (? billitonites) in Java.
(*g*) Indochinites, in Cambodia, Annam, and Siam.
(*h*) Colombian tektites, western South America.
(*i*) Ivory Coast tektites, from the Ivory Coast, Africa.

[1] Read at the British Association meeting at Nottingham in September 1937; abstract in Rep. Brit. Assoc. Adv. Sci., 1937, p. 356. A paper on similar lines was also read at the fifth annual meeting of the Society for Research on Meteorites at Denver, Colorado, in June 1937, and printed in Popular Astronomy, Northfield, Minnesota, 1937, vol. 45, pp. 504–507. [M.A. 7-78.] Compare C. Fenner, Australites, Parts I and II. Trans. Roy. Soc. South Australia, 1934, vol. 58, pp. 62-79, 6 pls.; 1935, vol. 59, pp. 125–140 [M.A. **6** 18, 208]; and L. J. Spencer, The tektite problem. Min. Mag., 1937, vol. 24, pp. 503–506.

In some cases tektite groups mentioned separately in this list may prove to belong to the one group. There are, however, seven or eight quite distinct groups separable according to (*a*) distribution, (*b*) chemical composition and physical properties, and (*c*) forms. Dr. L. J. Spencer, who is the leading British authority on these objects, has also investigated and recorded a remarkable occurrence of silica-glass in the Libyan Desert. There are other localities where the possibility of tektite occurrence has been suggested or is being investigated.

All the tektites agree in that they are objects composed of natural glass, scattered over the earth's surface in more or less limited areas, and having compositions, forms, and physical characters peculiar to each group. In almost all cases the areas of distribution are remote from any possible contemporary volcanic activity. Suess, Lacroix, and many others accept them as of cosmic origin, and classify them as 'glass meteorites'. Among Australian geologists, where the australites have naturally quickened interest and discussion, there is a general acceptance of the meteoritic theory of their origin. Australites, as well as each other separate tektite group, are accepted as a 'shower of glass meteorites'.

In the very extensive literature that has now accumulated concerning tektites, the following theories of their origin have been put forward and supported. That they were:

1. Relics from a prehistoric glass factory.
2. Cast in a mould (australites).
3. Volcanic bombs from terrestrial volcanoes.
4. Blebs cast forth from the mountains of the moon.
5. Relics of bubbles blown from terrestrial volcanic craters.
6. Formed by lightning by the fusion of sand in the air.
7. Colloidal bodies formed by the action of humic acids in soils.
8. Flung out when the moon was torn from the Pacific area.
9. Blebs swept from the tails of meteors.
10. Formed by the fusion of siliceous rocks by the impact of meteorites.
11. Molten blebs resulting from the combustion of a large light-metal meteorite.
12. Of all the theories that have been advanced perhaps the most positively worded was that of Hillebrand, that they were 'artificial products formed by man savage, or civilized, either by accident or by design'.

Most of these theories are incompatible with the facts of distribution, composition, and form types.

The australites stand out particularly by reason of the remarkable series of regular forms they present. Their distribution also appears to be more extensive than that of any other series, and it has been estimated that the total numbers involved over the whole area of the 'strewnfield' is between one and ten millions.

Distribution.—Australites are somewhat irregularly spread over the whole of southern Australia, south of a line joining Kyogle in New South Wales and Derby in Western Australia.

Composition.—SiO_2 70%+, Al_2O_3 13%+, FeO and Fe_2O_3 6%+, MgO 2%+, CaO 3%+, K_2O and Na_2O 4%+, traces of Mn, Ti, Ni, Co. Specific gravity 2·3–2·5.

Forms.—The greater number conform to a regular series that have been termed according to their shapes: buttons, lenses, ovals, boats, canoes, dumb-bells, and tear-drops. They have also a characteristic internal flow structure, and either a flange or rim (equatorial) separating two distinct types of surfaces. Important information concerning these objects is also to be gained from the surface-markings and the characteristic types of fracture.

Sizes.—The smallest known australite weighs 0·15 gram, and the largest 218 grams. The majority weigh about one gram, and that is the average weight of the Shaw collection. The largest known tektite is an indochinite of over 4 kilograms. The probable total weight of the whole of the australites that fell is between one and and ten tons.

Of the formidable list of theories given above, the greater number are ruled out by the facts of distribution, composition, and form. Their Pleistocene to Recent age rules out certain of the theories. Only two theories remain with any scientific support: (*a*) meteoritic impact fusing terrestrial material, and (*b*) the theory of cosmic origin.

In the case of the australites the evidence is totally against the theory of meteoritic impact. Australites are found lying on or near the surface, over practically the whole of the area of southern Australia, about 2,000,000 square miles. This area includes rocks of all types and compositions, but there is no corresponding variation in the composition or relative abundance of australites, nor in the types of forms. Vast numbers occur upon the Nullarbor plains, which are wholly limestone. The theory of human distribution is untenable. In the whole area here concerned there is only one place where meteoritic impact has occurred, and this occurrence has in no way affected the distribution of australites. The theory of meteoritic impact cannot, therefore, explain the occurrence and distribution of australites. It is suggested, therefore, that the only

heory which is in harmony with all the known facts is that of cosmic rigin.

Even with the acceptance of the cosmic theory of origin, many probems remain. It has been urged that the heat generated by atmospheric riction would be insufficient to melt the blebs. But the australites arry, in their external and internal structures, clear evidence of two eriods of melting. Each complete specimen likewise shows two distinct ypes of surfaces: an earlier or primary surface, partly destroyed and epresenting the rear part of the australite; and a later surface, secondarily developed, being the 'front' portion of the object, plus the flange where present). The two stages may not have been separated in origin y any measurable period of time, the one merging into the other during he brief term of their development.

It seems possible, following Suess, Lacroix, and others, that the ustralites originated within the atmosphere as a shower of siliceous lebs shed from a burning meteoritic body, at that moment assuming heir primary forms of sphere, dumb-bell, &c. Then, while still molten, hey sped spinning towards the earth, cooling on their rearward side, he heat of friction volatilizing some portion of the object and the ressure of the air on the re-heated forward portion giving the 'front' nd its fresh (secondary) shape, forming also the characteristic flange r rim.